BMO-TR-86-100
Flow Research Report No. 457

AD-A203 578

HYDRAULIC EXCAVATION SYSTEM
Phase II Final Report

J. J. Kolle

September 1988

Prepared for
HQ Ballistic Missile Office
Air Force Systems Command
Under Contract No. F04704-87-C-0032
Contract Period: 19 March 1987 - 21 August 1988

DISTRIBUTION STATEMENT A:
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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

ADA203578

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b. RESTRICTIVE MARKINGS: NONE
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: STATEMENT A: UNLIMITED - APPROVED FOR PUBLIC RELEASE
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): No. 457	5. MONITORING ORGANIZATION REPORT NUMBER(S): BMO-TR-88-100
6a. NAME OF PERFORMING ORGANIZATION: Flow Research, Inc. — 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: HQ Ballisitic Missile Office/MYET
6c. ADDRESS (City, State, and ZIP Code): 21414 - 68th Avenue South, Kent WA 98032	7b. ADDRESS (City, State, and ZIP Code): Norton AFB CA 92409-6468
8a. NAME OF FUNDING/SPONSORING ORGANIZATION — 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: F04704-87-C-0032
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.
65502F			

11. TITLE (Include Security Classification)
Hydraulic Excavation System Phase II Final Report (U)

12. PERSONAL AUTHOR(S)
Kolle, J.J.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Phase II Final Report	FROM 5-87 TO 8-88	1988 September	93

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
07	09	
14	01	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Rock Fracturing,
High Pressure Hydraulics,
Underground Excavation. JES

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The hydraulic excavation (HYDREX) system developed during this SBIR project is capable of non-explosive excavation of hard rock in any geometry required. The system is based on a tool which discharges a pulse of extremely high pressure water into a drilled hole.

The objective of the Phase II project was to develop the HYDREX concept into a practical excavation system. The first task of this project was to develop a quick opening discharge valve for the HYDREX tool. This work resulted in a poppet valve design which allows the tool to be repeatedly discharged. The prototype HYDREX tool developed in Phase II delivers a hydraulic impact greater than the most powerful impact hammers available.

Field testing of the prototype HYDREX systems was carried out in a hard volcanic rock quarry. The tool and a waterjet-assisted drill were mounted on turret assembly on which the HYDREX tool is indexed to a drill mechanism. The entire assembly was (continued)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL: ANDREW R. GHALI, LT, USAF	22b. TELEPHONE (Include Area Code): 714-382-2592 (AV 876) — 22c. OFFICE SYMBOL: HQ BMO/MYET

DD Form 1473, JUN 86 — Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

Abstract (continued)

mounted on a backhoe arm and was used to excavate a horseshoe shaped tunnel opening into an Andesite face. These tests demonstrated the system capability by excavating 6.85 metric tons of rock in less than 24 hours. Mechanization of the mucking process and simplified tool positioning will improve productivity to over 80 cubic meters of hard rock per day.

The HYDREX SBIR project has resulted in the development of a practical hydraulic excavation system with a variety of applications. The capital cost of the equipment is low compared to tunnel boring machines and the system may be quickly deployed to meet the needs of a complex tunneling or construction project. The greatest application will be for moderate size openings where conventional blasting is not an option and tunnel boring machines are too expensive. A number of commercial applications for the tool have been identified including deep level non-explosive mining, urban cosntruction, concrete demolition and boulder fragmentation.

APPROVAL PAGE

This Final Report was submitted by Flow Research, Inc., 21414 68th Avenue South, Kent, Washington 98032-1909, under contract F04704-87-C-0032 with the Ballistic Missile Office, AFSC, Norton AFB, CA 92409-6468. Lt Andrew Ghali, BMO/MYET, was the Project Officer in charge. This Final Report has been reviewed and is approved for publication.

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ACKNOWLEDGEMENTS

This program was made possible by the work of a number of dedicated engineers, designers and technicians. The project engineers were Jim Fort and Dave Monserud. Engineering design was provided by Sam Smith, Ken Theimer and Karl Voss. The field work was carried out by Paul Tacheron and Eckhardt Ullrich. The final report was edited by Kristie Hammond.

EXECUTIVE SUMMARY

The development of secure underground facilities for defense systems requires new techniques of excavating hard rock that overcome the limitations associated with the use of explosives or tunnel boring machines. Conventional drill and blast methods pose a hazard to nearby facilities or personnel through fly rock, dust generation, excessive ground motion and the release of toxic fumes. Tunnel boring machines provide cost-effective nonexplosive excavation of long, straight, circular tunnels but are inefficient for other excavation geometries.

The hydraulic excavation (HYDREX) system developed during this SBIR project is capable of nonexplosive excavation of hard rock in any geometry required. The system is based on a tool that discharges a pulse of extremely high pressure water into a drilled hole. Phase I research demonstrated that the pressures developed by the HYDREX tool are sufficient to fragment hard rock.

The objective of the Phase II project was to develop the HYDREX concept into a practical excavation system. The first task of this project was to develop a quick-opening discharge valve for the HYDREX tool. This work resulted in a poppet valve design that allows the tool to be repeatedly discharged. The prototype HYDREX tool developed in Phase II delivers a hydraulic impact greater than the most powerful impact hammers available.

Since the HYDREX tool is discharged into a small-diameter borehole, it was necessary to integrate a drilling mechanism into the excavation system. The tool and a waterjet-assisted drill are mounted on a turret assembly on which the HYDREX tool is indexed to a drill mechanism to ensure quick tool insertion. Hydraulic actuators on the turret provide for extension of the tool and drill, horizontal yaw motion and extension of a sting to locate the assembly securely on the rock face. The entire assembly is mounted on a backhoe arm for tool positioning.

Field testing of the prototype HYDREX system was carried out in a hard volcanic rock quarry. The system was used to excavate a horseshoe-shaped tunnel opening into an andesite face. This material was found to have a compressive strength ranging from 74 to 265 MPa. Excavation productivity and efficiency were measured by timing the excavation steps and weighing the material removed. These tests demonstrated the system capability by excavating 6.85 metric tons of rock in less than 24 hours. Most of the work involved was devoted to removing fragmented rock and tool positioning.

EXECUTIVE SUMMARY (Cont.)

Mechanization of the mucking process and simplified tool positioning will improve productivity of a single tool to over 80 m^3 of hard rock per day.

The HYDREX SBIR project has resulted in the development of a practical hydraulic excavation system with a variety of applications. The capital cost of the equipment is low compared to tunnel boring machines, and the system may be quickly deployed to meet the needs of a complex tunneling or construction project. Air Force applications for the HYDREX system include construction or expansion of hardened ballistic missile launch sites and command centers. The greatest application will be for moderate-sized openings where conventional blasting is not an option and tunnel boring machines are too expensive. The flexibility of the HYDREX system will greatly reduce the cost of moderate-sized facilities in hard rock, thereby expanding the range of options available to Air Force planners.

A number of commercial applications for the tool have also been identified including deep-level nonexplosive mining, urban construction, concrete demolition and boulder fragmentation. A modified version of the HYDREX tool is now being commissioned by the operator of the Three Mile Island nuclear power plant as a means of fragmenting the melt products pooled in the bottom of the reactor vessel.

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SECTION 1. INTRODUCTION

The invention of nitroglycerin and related high explosives in the nineteenth century made large-scale mining of hard rock possible. Detonating explosives shatter any type of rock and are relatively simple to use. However, high explosives have several limitations: continuous excavation is not possible, blasting in urban areas is restricted or banned altogether and high-explosive blasting may not be permitted in excavations containing combustible gas or dust. The only nonexplosive technique widely used for hard rock excavation is the tunnel boring machine, which is limited to producing a straight circular opening. This SBIR project has been directed towards the development of a Hydraulic Excavation (HYDREX) tool to provide an alternative to explosive excavation of hard rock.

The HYDREX tool consists of a pressure vessel with a fast-opening valve or rupture disk that discharges through an outlet tube into a drilled hole in a rock face. The Phase I study showed that the pressure pulse produced by the tool causes multiple fracturing of the rock and fragmentation. The HYDREX tool may thus be used as the basis for a hard-rock excavation system. These tests led to the Phase II study to demonstrate the excavation performance of a prototype HYDREX tool. The Phase II study was divided into the five tasks shown below.

- Task 1. Valve Development
- Task 2. Concrete Block Testing
- Task 3. Excavation System Design and Fabrication
- Task 4. Field Testing
- Task 5. Commercial System Conceptual Design

To build a prototype system for field testing, it was first necessary to develop a reliable discharge valve that met the theoretical requirements for a pressure pulse. This was the first task of the Phase II work, and it is described in detail in Section 3.

Phase I fragmentation tests were all carried out on unconfined boulders of hard andesite. Boulders are relatively easy to fragment because of the presence of free surfaces. Before an excavation system based on the HYDREX tool could be designed, it was necessary to learn how well it would fragment confined rock. These tests, which are discussed in Section 4, were carried out on a block of high-strength reinforced concrete that simulated a confined rock face.

Testing in the confined concrete led to a design for a prototype HYDREX excavation system (see Section 5). This design incorporates a waterjet-drill mechanism and actuators for drilling, tool insertion and blasting. A mounting system and controls were designed to allow the HYDREX assembly to be mounted on a backhoe for field testing. This system was built and tested on a second block of reinforced concrete in our laboratory.

The HYDREX system was tested in a hard rock quarry where an 8-foot-high tunnel opening was excavated. These field tests, which are described in Section 6, made it possible to determine system productivity, energy consumption and component reliability. The results of the field tests were used to develop a commercial HYDREX system design (see Section 7) and to estimate its performance in comparison with conventional excavation systems.

SECTION 2. BACKGROUND

A number of attempts have been made in the past to develop alternatives to conventional excavation techniques. Hydraulic fracturing has been particulary attractive in past work. The tensile strength of most rock is less than 20 MPa, which is easily obtained with conventional hydraulic equipment. Simply pressurizing a borehole results in a fracture parallel to the borehole axis, which is not effective for excavation of a face. Fractures can be induced perpendicular to the borehole by notching, as described in Kolle (1983), but field tests have shown that the pressures and flow rates available are too low to result in effective excavation (O'Hanlon and Kolle, 1986).

A series of tests carried out at Sandia National Laboratories (Schmidt et al., 1980) showed the effect of pressurization rate on the transition from hydraulic fracturing to multiple fracturing and to explosive rock fragmentation. This work has led to the development of a hydraulic tool capable of generating multiple fractures in hard rock (see Figure 1). Such a device was built in the Phase I feasibility study. Bench testing demonstrated the device's ability to generate peak pressures and pressure rise times in a confined hole similar to those associated with a deflagrating explosive, although the pressure decay curve is more rapid. Laboratory tests showed that the tool was capable of fragmenting unconfined rock.

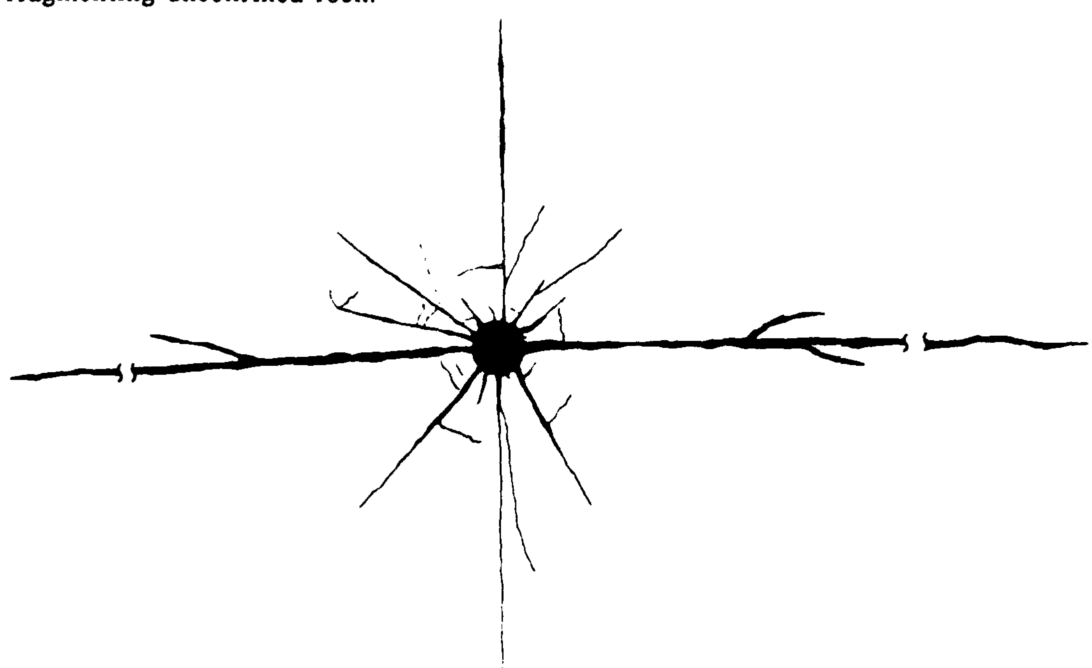


Figure 1. Multiple Fracturing

High explosives fragment rock in two steps. The detonation generates an intense compressive shock wave that travels out from the borehole. Near the borehole, the pressures may be high enough to crush porous rock. Fourney et al. (1983) have shown that as the shock travels away from the borehole it will interact with pre-existing voids and cracks and will generate high shear and tensile loads, which will cause these flaws to grow. Larger flaws such as joints will also modify the shock wave so that shear and tensile loads are produced, which will cause fracture propagation. It is generally thought that once these fractures start to connect to each other, the gaseous products from the explosion enter the fractures and play a dominant role in driving them to completion (Porter and Fairhurst, 1971).

The situation is modified for deflagrating explosives or propellants. These are distinguished from high explosives in that they burn rather than detonate. The rate of burning and hence the pressurization rate is consequently several orders of magnitude slower and is measured in milliseconds rather than microseconds. The peak pressures produced are also much lower, generally on the order of 0.1 to 1.0 GPa. The fracturing produced by a deflagrating explosive can be explained by tensile loading on the borehole wall due to the confined gas pressure.

A high-energy gas fracture experiment described in Schmidt et al. (1980) and in Taylor et al. (1984) evaluated the type of fracturing produced by different types of explosive or propellant charges in ash-fall tuff. The number of fractures produced was related to the rate of pressurization as indicated in Figure 2. At low pressurization rates,

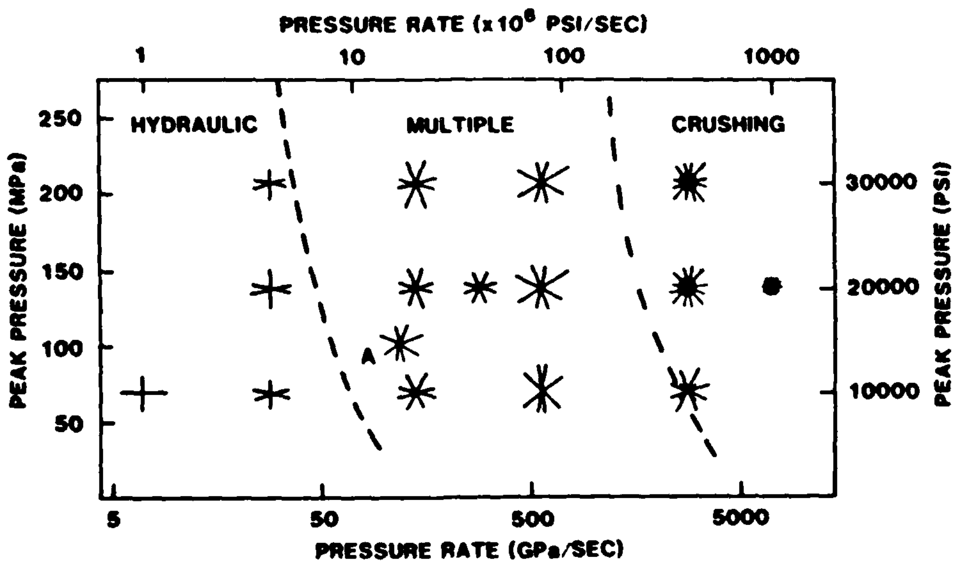


Figure 2. High-Energy Gas Fracture Test Results

the loading is quasistatic and a single hydraulic fracture plane is produced oriented perpendicular to the minimum principle stress. The loading rate was increased by using propellant charges, and multiple fractures were observed. At the higher load rates associated with high exlosives, crushing of the borehole wall and extensive multiple fracturing was observed. In conjunction with these tests, a technique was developed by Swift and Kusubov (1983) to induce multiple fractures hydraulically. These tests showed that at loading rates of 10 GPa/s or faster, multiple fractures were induced in a dense sandstone.

Multiple fractures are initiated due to dynamic tensile stresses on the borehole wall. Cuderman et al. (1981) proposed a borehole diameter scaling relationship for multiple fracturing based on the peak pressures obtained and the compressive wave velocity. This is modified here using the Rayleigh wave velocity and fracture initiation pressure to obtain characteristic time scales. We assume that multiple fracturing occurs when some characteristic time related to the fracture pressure, P_f, and the pressurization rate, P', becomes comparable to the time required for a stress wave to travel around the surface of the borehole. The pressurization rate can be estimated from the pressure rise time, t_p, and the peak pressure, P_p :

$$P' = P_p/t_p \tag{1}$$

Haimson and Fairhurst (1970) showed that the fracture pressure is equal to the tensile strength of the rock in the case of a pressurized borehole in a variety of unconfined rock types and is typically on the order of 10 MPa.

The characteristic travel time is related to the circumference of the borehole, and the condition for multiple fracturing becomes

$$t_p P_f/P_p \approx \pi D/V_r \tag{2}$$

where D is the borehole diameter and V_r is the Rayleigh wave velocity (Bullen, 1963):

$$V_r = 0.92 \sqrt{G/\rho} \tag{3}$$

where G is the shear modulus and ρ is the rock density. If, for example, $G = 25$ GPa and $\rho = 2500$ kg/m^3, then the Rayleigh wave velocity is about 3500 m/s and the characteristic time for a 25-mm borehole is 22 microseconds.

Hydraulic pumps that routinely provide pressures of 400 MPa at flow rates of 0.2 liter/s are now commercially available. If a pressure pulse of this magnitude with a

sufficiently short rise time could be produced, a tool capable of inducing multiple fracturing in hard rock would be feasible. The required rise time at 400 MPa in a 25 mm borehole assuming a fracture initiation pressure of 10 MPa is about 1 millisecond. A hydraulic tool that provides such a pulse is described below.

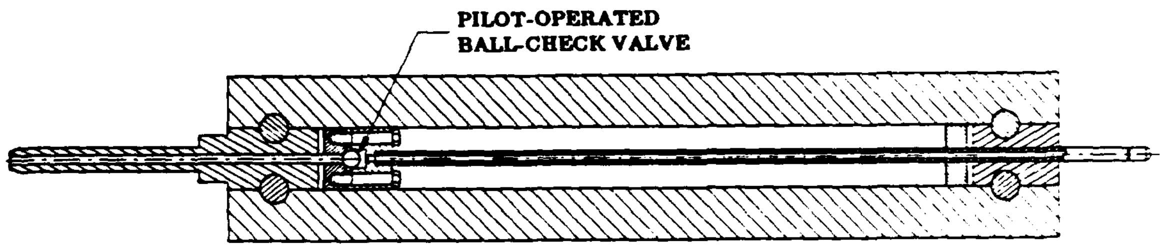


Figure 3. HYDREX Tool

The HYDREX tool (Figure 3) consists of a heavy-walled pressure vessel rated for operation at 400 MPa, a pilot-operated discharge valve and an outlet tube (see specifications in Table 1). The vessel is charged to 400 MPa through a flexible hose from a high-pressure pump. At this pressure, significant energy is stored in the compressed volume of water. When the inlet line is vented, the discharge valve opens and the vessel discharges through the outlet tube.

Table 1. Prototype HYDREX Tool Specifications

Operating Pressure	380 MPa
Internal Volume	2.2 liters
Discharge Volume	0.25 liter
Stored Energy	42 kJ
Outlet Diameter	11 mm
Borehole Diameter	25 mm
Initial Flow Rate	58 liters/s
Mass	180 kg

The amount of energy stored in the tool can be calculated from the bulk modulus of water and the pressure. According to Streeter (1975), the bulk modulus of water increases linearly with pressure as

$$K_m = K_o + bP \tag{4}$$

where $K_o = 2.0$ GPa and $b = 6.0$. The volume change due to increasing the pressure from atmospheric pressure to a pressure P is

$$dV/V_o = (1/b) \ln (1+bP/K_o) \tag{5}$$

and the work done is

$$J_s = (V_o/b^2) [bP - K_o \ln (1+bP/K_o)] \tag{6}$$

The total stored energy in a 2.2-liter vessel pressurized to 380 MPa is 40 kJ, which is equivalent to about 3 gm of TNT. The volume of water released during discharge is 250 ml (see Figure 4).

In the Phase I study, a measurement was also made of the pressure history of a shot into a rock during fracturing. These measurements showed that the peak pressure

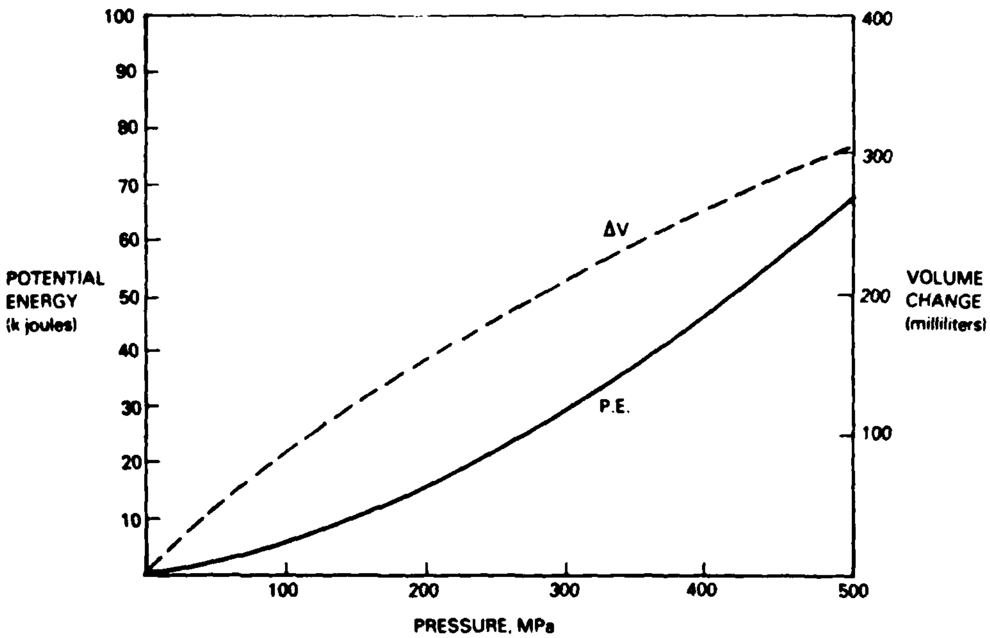


Figure 4. Volume Change and Stored Energy for the 2.2-liter Pressure Vessel Used in the Tests

developed in a rock cavity is limited by the borehole breakdown pressure, which is much lower than the peak pressures observed in the test chamber. In these tests, the axial acceleration of the tool was measured with an accelerometer.

Acceleration was used to determine the integrated pressure over the bottom of the hole, since the mass of the tool is known (see Figure 5). The mean pressure over the bottom is only about 60 MPa, which is considerably less than the peak pressures of 250 to 300 MPa observed in the pressure chamber tests. Presumably, 60 MPa represents the borehole breakdown pressure or dynamic tensile strength of this andesite.

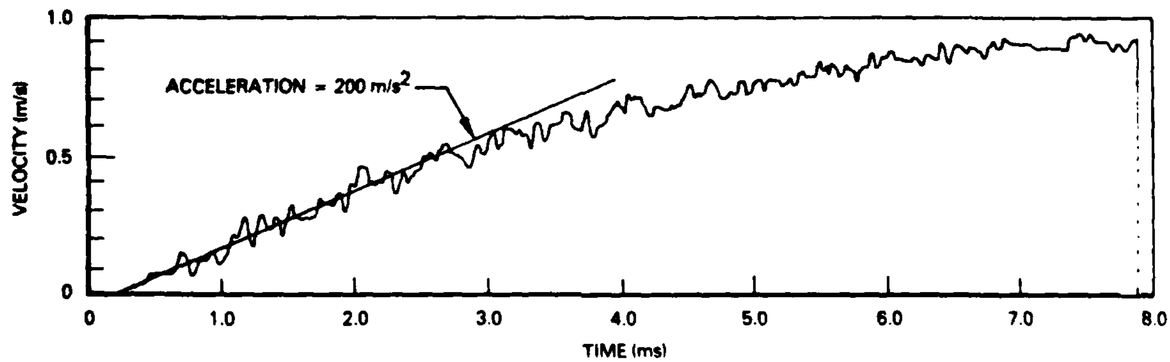


Figure 5. Axial Acceleration of Tool in Andesite

The testing described above demonstrated the applicability of intermediate-rate hydraulic loading to the multiple fracturing and fragmentation of unconfined boulders. Experience with other nonexplosive techniques and with explosives has shown that removal of confined rock is considerably more difficult (Rhyming et al., 1980). The ease of fragmentation in unconfined rock is partly due to simple geometric considerations.

The multiple fracture pattern consists of cracks radiating from the borehole axis and conical cracks extending downwards from the bottom of the hole. This pattern is quite effective at fragmenting a boulder but does not necessarily result in removal of rock from a confined face.

SECTION 3. VALVE DEVELOPMENT

During the Phase I feasibility study, all of the testing was carried out using a burst disk to discharge the tool. At the end of this study, a prototype valve capable of discharging the tool was developed. The use of a valve greatly reduces the time between shots and is essential to a commercial system. In Phase II, further valve development was carried out, resulting in a reliable valve capable of producing pressure pulses equivalent to those produced by the burst disk. Figure 6 illustrates the four valve designs tested in Phase II along with the burst disk discharge assembly. All of these valves are pilot operated by venting the inlet line to the tool.

Pressure rise times and peak pressures for these valves were obtained by discharging them into a vented chamber with an inside diameter of 27 mm as shown in Figure 7. The discharge tube diameter in all of these tests was 25.4 mm, which leaves a 0.8 mm annular gap. The dynamic pressure response was measured with a quartz piezo-transducer in two locations. This transducer is capable of measuring frequencies of up to 100 kHz. Pressure profiles were recorded on a digital oscilloscope with a maximum sampling rate of 2 MHz.

Initial tests were carried out with the transducer located on the hole bottom. In one of the tests with a burst disk, the fragments from the disk impacted the transducer and caused failure. The transducer was then moved to a location on the side of the hole immediately above the bottom. No apparent differences in pressure profiles due to the change in transducer position were observed. Except where noted all of the tests were carried out in a dry chamber.

Pressure profiles from six burst disk discharges at 380 MPa are shown in Figure 8. In four of the tests, there is a large initial spike followed by ringing at a frequency of 10 kHz. In the other tests, the pressure spike and ringing are not observed. The origin of the pressure spike is not known. As will be seen, the burst disk pressure profiles are less repeatable than any of the valves tested. This may be caused by variability in the burst disk failure mechanism.

The first valve design incorporated a ball enclosed in a cage connected to the vent line. The ball seats on the opening to the discharge tube like a check valve. During filling of the tool, water flows around the ball in an annular gap between the ball and the cage. When the inlet line is vented, a high-pressure drop is created across the ball through this annular gap. This pressure drop is sufficient to lift the ball off of its seat, resulting in a discharge.

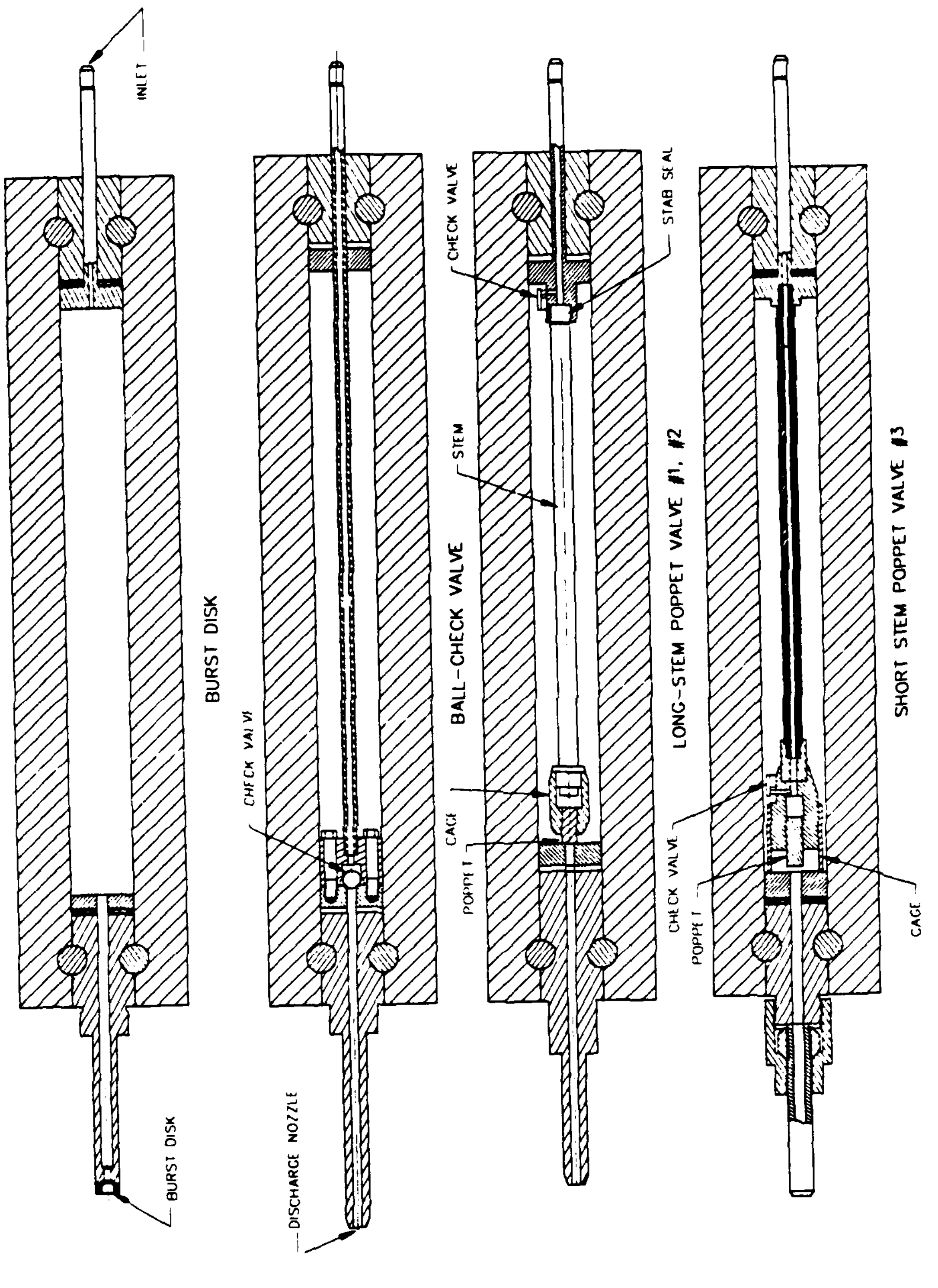


Figure 6. Burst Disk Assembly and Discharge Valve Designs

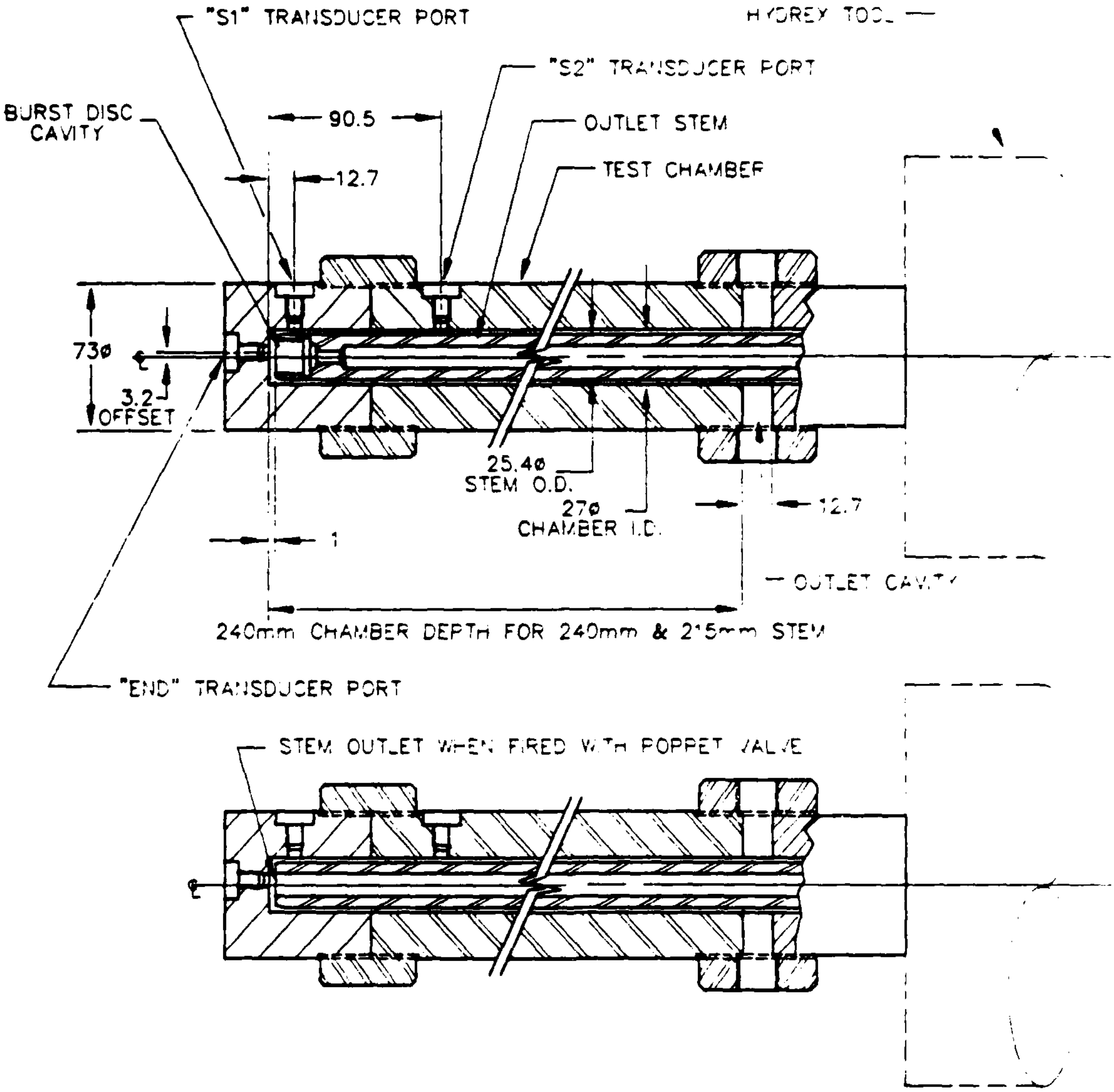


Figure 7. Pressure Chamber for Rise Time Tests

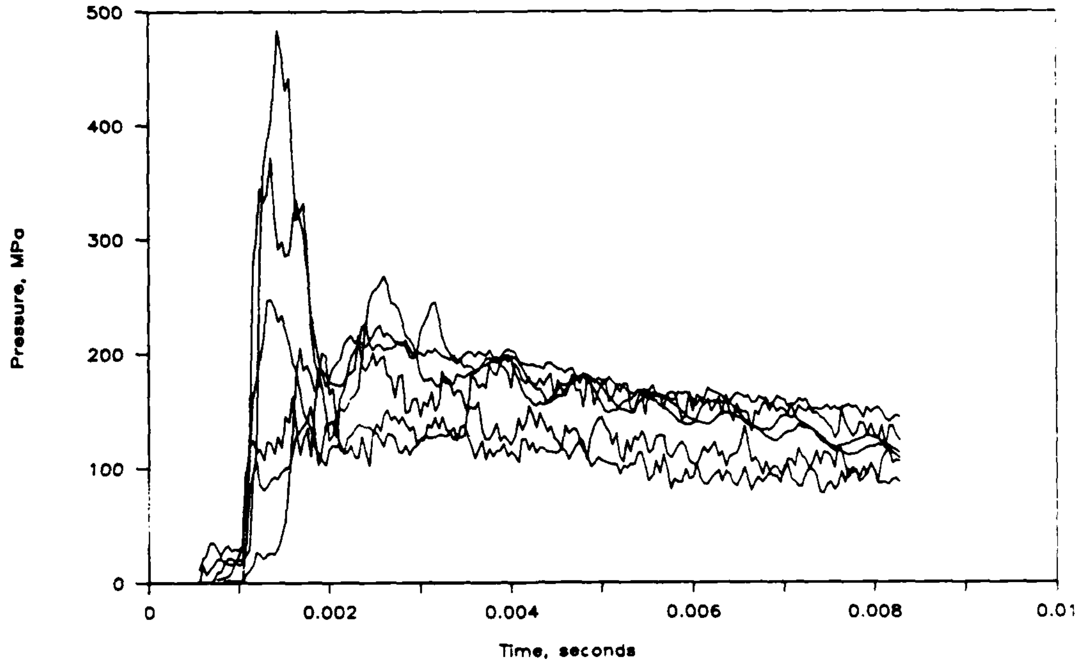


Figure 8. Pressure-Time History for Discharge into 27-mm Test Chamber with Burst Disk

Six pressure profiles for discharge from this ball-check valve design are shown in Figure 9. Four of these profiles were obtained with the pressure chamber prefilled with water. The pressurization rate for these tests is lower than for the two tests carried out in a dry pressure chamber. Figure 10 illustrates the difference in the initial pulse profile. When the HYDREX is fired into a dry hole, the pressure rise is very rapid, corresponding to impact of the high-velocity fluid on the transducer. The pressurization rate of this pulse is 1625 GPa/s. In a water-filled hole, the rise time is more gradual (267 GPa/s) since the water cushions the impact of the discharge. The rapid pressure pulse associated with discharge into a dry hole would be expected to produce better multiple fracturing.

Peak pressures and pressurization rates for the ball-check valve design are within the range required for multiple fracturing as can be seen in Table 2. However, the pressure pulse from this valve declines more rapidly than that for a burst disk discharge. This is because some of the tool energy is lost through the vent line. In addition, the ball-check valve design is subject to severe wear on the ball and cage, which limits the life to less than 100 firings.

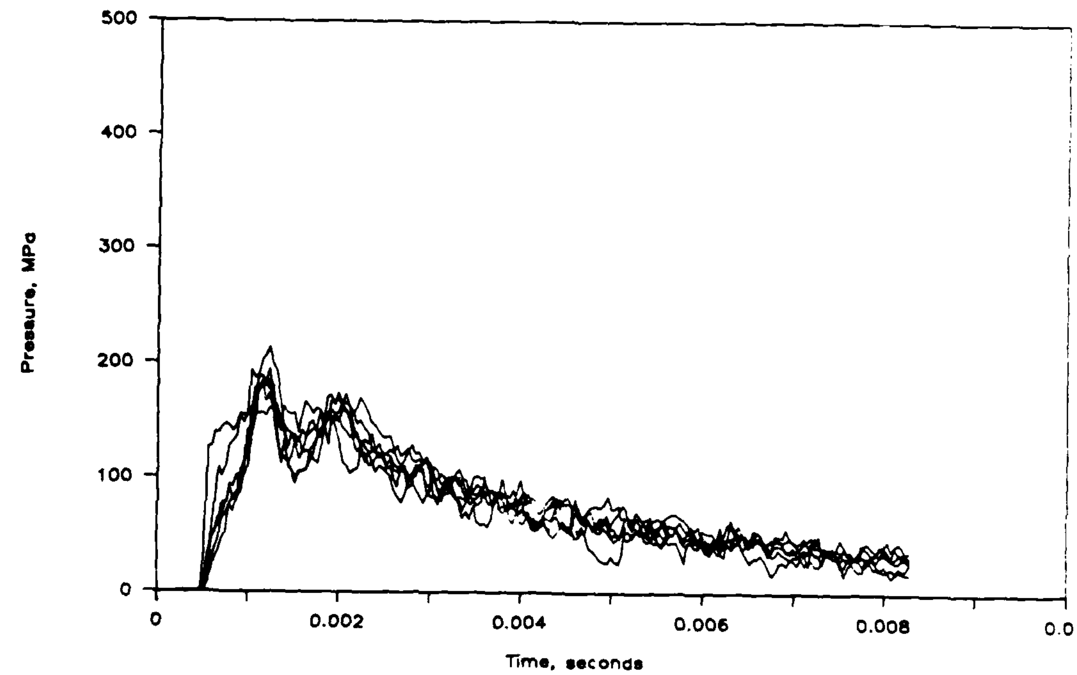


Figure 9. Pressure-Time History for Discharge with Pilot-Operated Ball-Check Valve

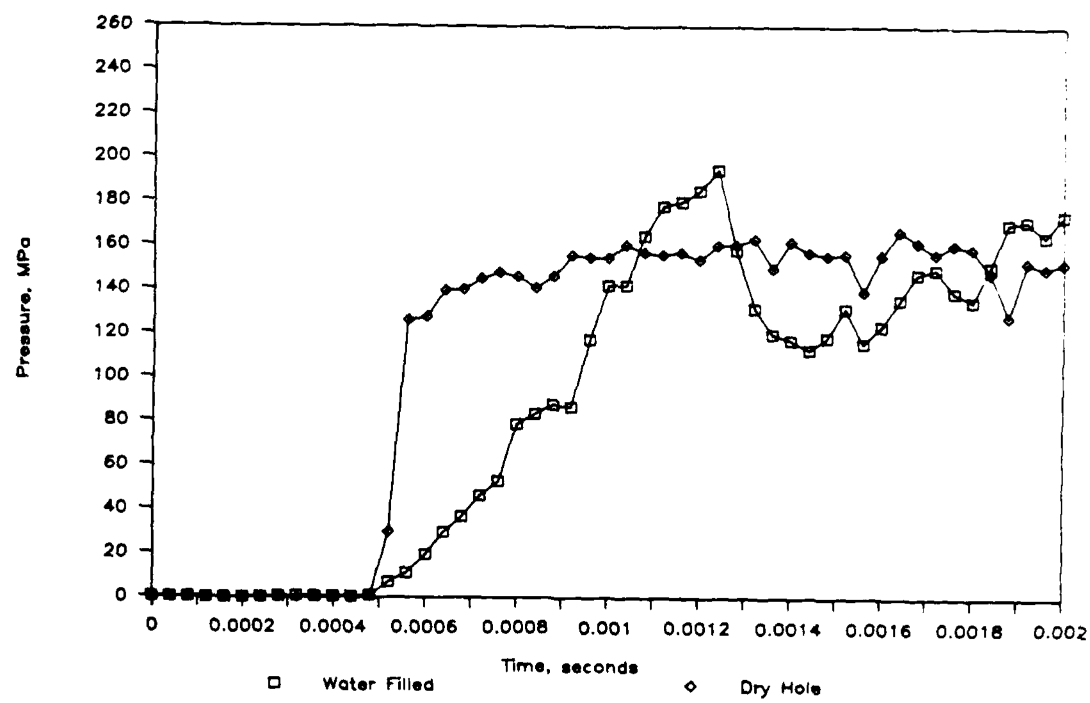


Figure 10. Detail of Pressure Rise Time for Two Tests of Ball-Check Valve Design

Table 2. Test Chamber Pressure Results

Valve Type	Discharge Pressure (MPa)	# Shots	Average Peak Pressure (MPa)	Pressurization Rate (GPa/s)
Burst disk	380	6	251	1333
Ball-check	380	12	223	349
Long-stem poppet, #1	380	11	194	79
One-piece poppet, #2	380	9	178	71
Short-stem poppet, #3	414	4	354	1050

The first two designs developed for the Phase II project relied on a long-stem poppet to replace the ball valve design. In these two designs, a separate check valve is provided to fill the tool. A poppet provides sealing at the discharge outlet. When the tool is vented, the entire stem moves until the poppet is unseated. At this point, the poppet is intended to accelerate upwards into its cage allowing rapid discharge of the tool. In practice, however, the cage cavity is filled with water at high pressure, and the poppet never moves into it. The discharge requires that the entire stem move to open the valve. Two versions of this design were tested. The first was unreliable because of leakage in the stem. In the second design, the number of parts in the stem was reduced to two. The second design is referred to as a one-piece design, since the poppet cage and stem are machined as a single part.

Discharge curves for the long-stem poppet designs are shown in Figures 11 and 12. While peak pressures are comparable to that of the ball-check valve design, the rise times are much longer. The slow pressurization rate is due to the time required to accelerate the entire stem assembly in this design. The change to a one-piece design reduced the variability in discharge seen in the first design, but the general profile is similar. Presumably, variability in the first valve design was caused by leakage. Long-term pressures are comparable to that for the ball-check valve design, but significantly lower than for a burst disk discharge.

The pressure profiles for the long-stem poppet valve are not acceptable for multiple fracturing. A new pilot-operated poppet valve design was therefore developed to overcome these problems (poppet valve #3). This design is similar to the ball-check valve design in that the poppet is retracted by venting the cage that holds it. The design differs in that the poppet is sealed inside the cage so that no energy is lost by venting the tool. This requires that the tool be filled through a separate check valve as in the long-stem poppet design.

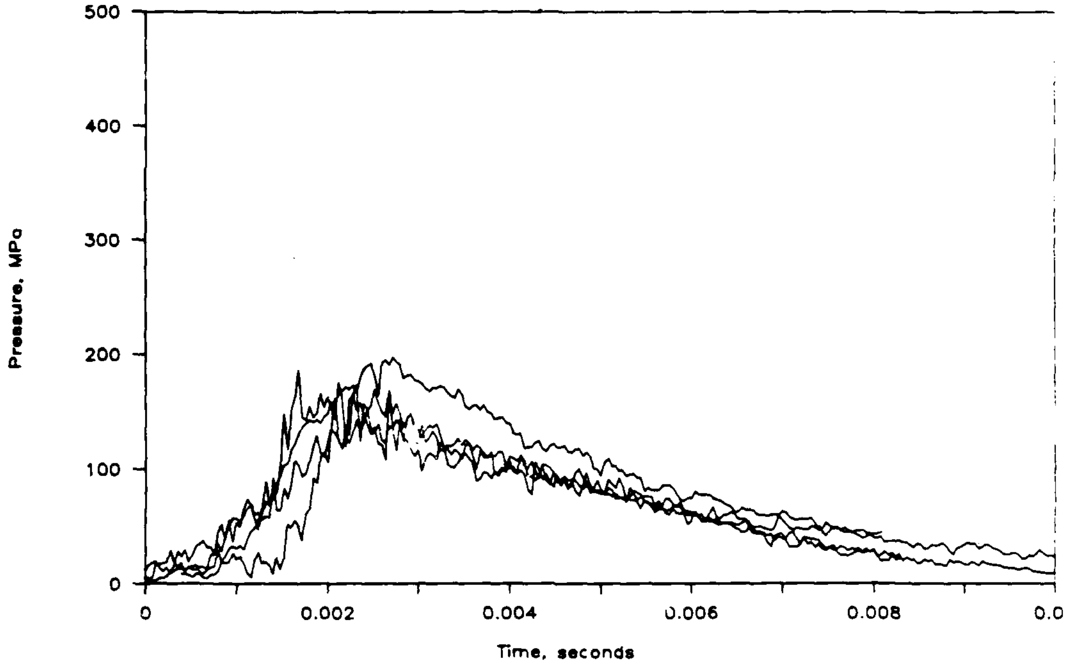


Figure 11. Pressure-Time History for Discharge with Poppet Valve #1 - Long Stem

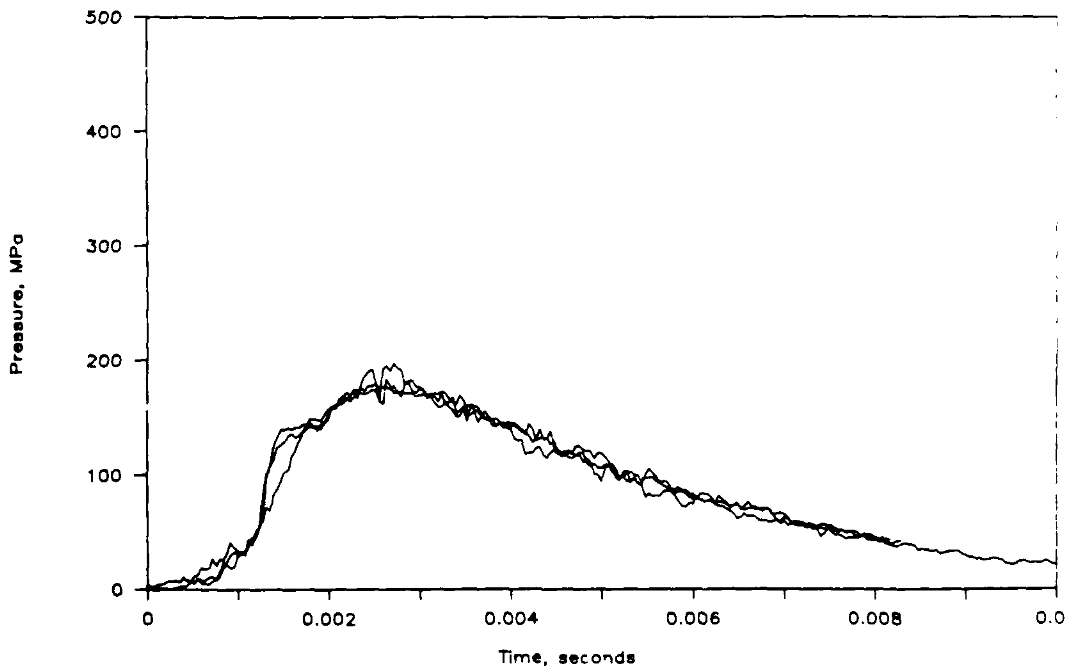


Figure 12. Pressure-Time History for Discharge with Poppet Valve #2 - Long Stem, One Piece

Three discharge pressure profiles for this poppet valve design are shown in Figure 13. These profiles demonstrate a very repeatable, high-rate pressure pulse with the 10-kHz ringing seen in some of the burst disk observations. Peak pressures and pressurization rates are comparable to those of a burst disk discharge. Long-term pressures are slightly lower. The loss of some energy is unavoidable in a valve design because the valve must occupy some of the internal volume of the tool.

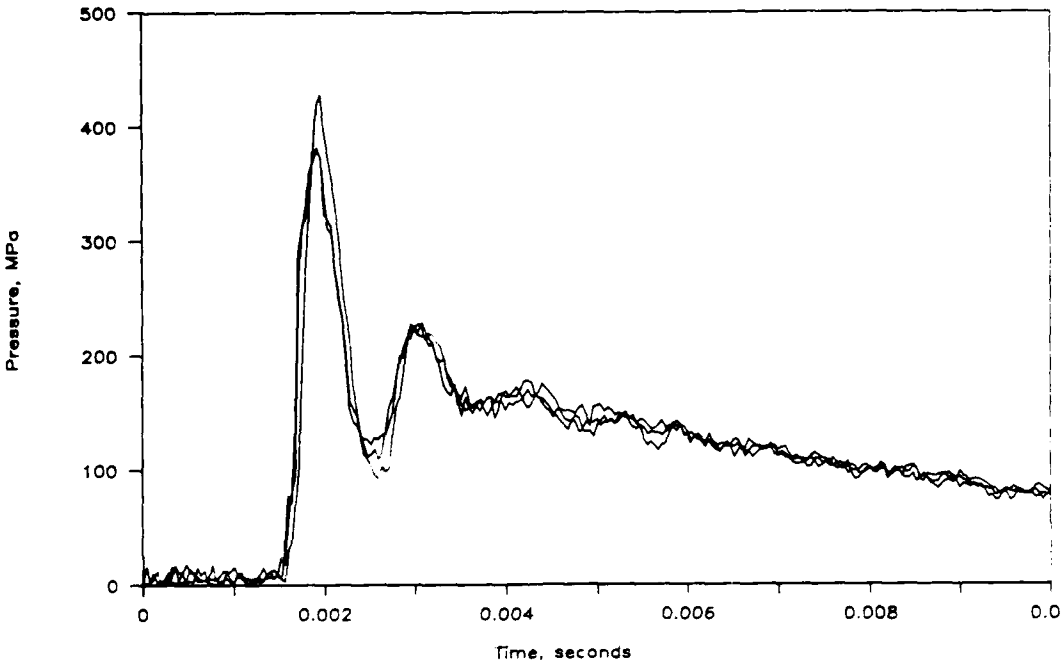


Figure 13. Pressure-Time History for Discharge with Poppet Valve #3

Several tests were carried out with poppet valve #3 with the end of the discharge tube located 25 mm off of the bottom of the test chamber. Results from two of these tests are shown in Figure 14. In this configuration, the pressure pulse peaks are just as high but the long-term pressures are lower. In one case, the pressure drops to zero abruptly after 7 milliseconds. The pressures are also less uniform than for the bottomed nozzle discharge configuration used in all of the other tests. Presumably, the peak pressure reflects the stagnation pressure of high-velocity fluid in the cavity at the bottom of the hole while it is filling. When full, the pressure declines more rapidly because some of the energy has been lost in expansion of the water to fill the cavity.

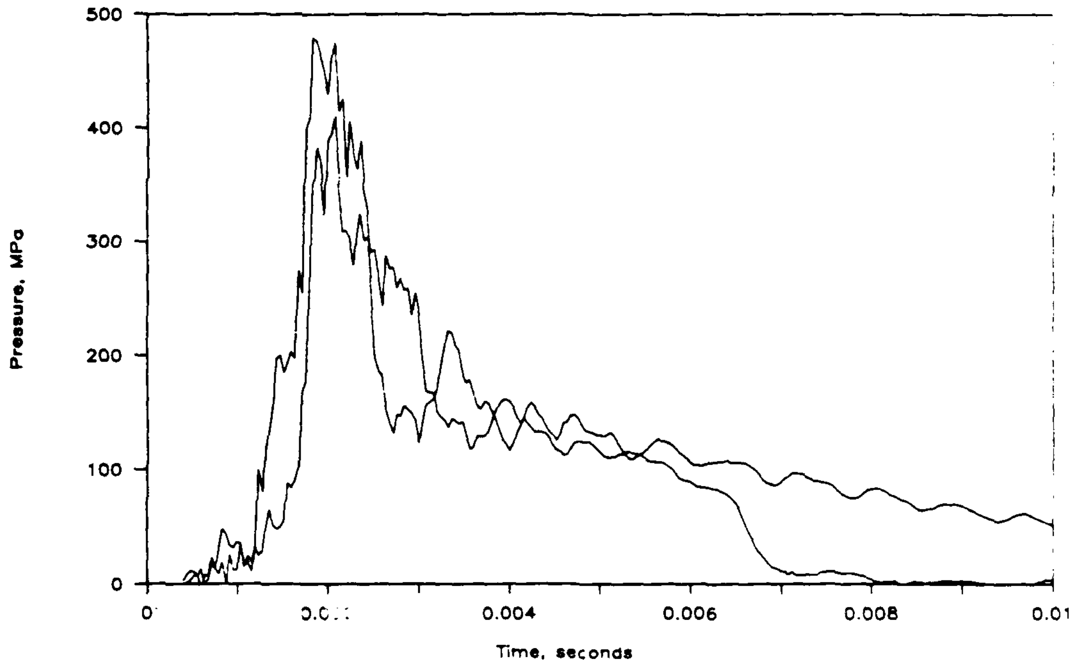


Figure 14. Pressure-Time History for Discharge with Poppet Valve #3 - 25 mm from Hole Bottom

SECTION 4. CONCRETE BLOCK TESTING

A major goal of the second phase of this project was to develop a means of excavating confined rock with the HYDREX tool. Thus, a large amount of testing was devoted to rock in the confined condition. A confined rock sample is defined as rock that is restrained from outward expansion or displacement. This is compared with pressurized confinement, where the rock is not only restrained, but also under a state of imposed compressive stress. Pressurized confinement is typical of all underground excavations; however, the confining pressure does not significantly affect the excavation process except at great depths. For this reason, and because pressurized confinement is difficult to implement in the laboratory, all of the Phase II tests dealt only with confinement and not pressurized confinement.

In Phase I, the confined state was simulated by potting rock boulders with concrete in a plywood box. Boreholes were drilled vertically into the exposed rock faces, and the HYDREX tool was used to fracture the rock. Although many radial fractures were produced at each borehole, the confinement caused by the concrete made material removal impossible for the most part. (These results alone suggest a reasonable simulation of true confinement.) One problem with this method was that cracks propagated to, and opened up at, the base and walls of the concrete block. Only the plywood box kept the pieces together. These open cracks probably impaired the tool's effectiveness by reducing peak pressures. Therefore, a better system for simulating confinement was needed.

In Phase II, two changes were made to better represent a confined rock sample. Again, a concrete crib was used; however, this time the block's sides and base were reinforced with steel bar. Thus, even though a crack might propagate to the boundary, the reinforcement would keep it from opening. The top of the block was left free of reinforcement to provide an entry for excavation. The second change was that, rather than pot rocks into the crib, the fracture tests were carried out directly in the concrete. Concrete is easier to work with than boulders and provides a more uniform material for testing. For high-strength concrete, the uniaxial compressive strength is equal to that of the previous andesite test rock. Moreover, the lack of preexistent cracks makes the test in concrete more difficult.

4.1 Experimental Layout

The concrete block used for the first test was 1.2 m square and 0.6 m deep. The reinforcing bar layout is illustrated in Figure 15. The concrete was a high-strength pea gravel aggregate mix with a reported 7-day compressive strength of 45 MPa and a 28-day strength of 62 MPa. A percussive drill was required to drill smooth-gauge boreholes in the concrete. A waterjet-assisted drill (ADMAC JET-MINER^{TM}) overcut the gauge and produced a ragged hole. The percussive drill was a Gardner Denver Model E-981 using a tapered drill steel and a 31.8 mm brazed cross bit that had been ground to a 26.3-mm diameter. Handheld drilling produced adequately straight holes and, therefore, a mechanical support was not normally used.

The HYDREX tool configuration was the same throughout this test. The shock tube had a 25.4-mm outside diameter and a 9.5-mm inside diameter and was 203 mm in length. The discharge valve was the ball-cneck valve design and was normally discharged at 27 MPa hydraulic pressure, giving an approximate accumulator pressure of 380 MPa.

Figure 15. Reinforcing Rod Cage for Confined Concrete Block

4.2 Experimental Approach

As mentioned above, prior attempts to liberate rock from a confined test crib with the HYDREX had been largely unsuccessful. Fractures were produced, but the fractured rock was locked together like a "puzzle" that inhibited the extraction of any one piece. Effective removal would apparently require a much higher energy blast, which would produce much finer fragmentation and acceleration of the fragments from the excavation. However, since finer fragmentation is inefficient and not normally desired, and, moreover, since the HYDREX tool has limited stored energy, a different approach was required.

Johansson and Persson (1970) have reported on research showing that the removal of a given amount of rock using a borehole drilled perpendicular to a flat surface required 10 times the breaking energy as the same borehole drilled parallel to the free surface. This is the principle behind benching in open excavations. In confined excavations, for example, driving a tunnel, the only free face is the working face. It is possible to produce a free face around the perimeter of the tunnel by a tunnel profiling machine, such as an abrasive-waterjet, but this would add considerable time and expense to an excavation.

In tunnel blasting, the central part of the pattern is often drilled at an angle of up to 45 degrees pointing in towards the tunnel axis. These holes are set without a delay timer so that they are the first to detonate. This excavates a conical cavity in the center of the face. The charge delay time is increased as the radius increases so that successive detonations blast the rock into the cavity created earlier. This approach was used for the fracture tests with the HYDREX tool. The objective of these tests was to determine fragmentation energy and the effects of borehole geometry in confined rock.

4.3 Results

Over the 2-1/2-week testing period, 388 kg of concrete was excavated, constituting approximately 25 percent of the test block interior. This required drilling and blasting a total of 41 boreholes. Borehole inclination was found to have a very strong influence on the ability to excavate confined rock successfully. Table 3 presents a detailed account of borehole geometry and blast record for each borehole location. Figure 16 shows a composite of all borehole locations. Note that several excavation levels are represented.

Table 3. Results of HYDREX Tests in 1.2-m Concrete Block

Hole No.	Depth (mm)	Angle (deg)	No. Shots	Removed Wt.(kg)	Cum. S.E. (MJ/m^3)	Remarks
1	134	65	4	0	****	radial cracks only
2	165	48	3	36	18.5	
3	114	44	1	5	18.5	
4	127	45	5	17	21.4	
5	165	48	2	8	21.8	
6	165	47	4	10	24.2	
7	152	46	3	5	26.2	
-	-	-	1	14	29.8	
8	152	45	1	24	23.9	2 kg from drilling
9	159	73	5	24	23.1	
10	152	58	1	5	23.0	
11	134	56	6	8	25.8	8 kg from drilling
12	127	67	-	-	25.8	not fired
13	152	75	5	1	29.1	
14	134	90	1	27	25.0	
15	165	79	7	1	28.8	tool only half in
16	178	78	2	15	27.5	shot before #15
17	152	78	4	0	29.6	
18	165	53	5	0	32.2	leakage to #13,#17
19	152	87	4	5	33.4	
-	-	-	15	26	36.3	firing into cracks
20	89	75	2	3	36.8	1 kg from drilling
21	127	90	3	0	38.1	
-	-	15	3	0	39.4	
-	-	-	6	14	39.5	firing into cracks
22	134	62	6	0	42.0	$P << 350$ MPa
23	134	67	-	-	42.0	not fired
-	-	15	3	0	43.2	
-	-	22	2	14	41.5	
-	-	23	2	6	41.4	
-	-	11	1	17	39.0	
24	134	75	2	0	39.8	
25	152	72	1	5	39.4	
26	134	90	2	4	39.5	
27	134	70	3	0	40.5	
28	134	75	3	12	39.8	
29	152	50	2	1	40.4	
30	152	55	2	9	39.8	
-	-	11	3	0	40.8	
31	134	80	1	7	40.1	
32	152	75	1	4	40.0	
33	152	70	1	4	39.9	
34	134	60	3	2	40.5	
35	127	60	3	22	38.7	
36	134	50	-	-	38.7	not fired
37	152	60	-	-	38.7	not fired
38	152	85	4	15	38.2	
-	-	24	1	0	38.5	
39	152	45	4	8	8.7	100-mm insertion
40	127	80	3	11	38.3	
41	102	50	3	15	37.5	
-	-	-	1	2	37.6	firing into cracks

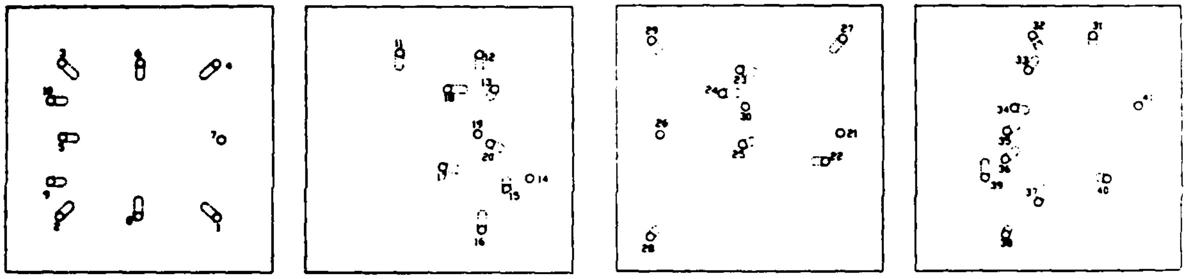


Figure 16. Concrete Block Excavation Pattern

The borehole inclination, measured relative to the top surface of the block, was varied between 45 and 90 degrees. The first four boreholes were drilled at the four corners of the block surface, all inclined away from the center. The borehole depths and inclination angles all differed: 134 mm at 65 degrees; 165 mm at 48 degrees; 114 mm at 44 degrees; and 127 mm at 45 degrees, respectively. The first borehole was apparently too steep to permit a chip to break out. as only radial cracks were formed. The remaining three all resulted in broken out material. The inclinations were approximately equal at 45 degrees. The amount of mass removed varied roughly with depth.

After the first four holes, the next dozen were drilled in a pattern around the perimeter of the excavation, always inclined so that the chips would form toward the center. The net result after the first 16 holes was the removal of the first layer of concrete (approximately 130 mm deep). Subsequent holes were selectively drilled in the interior of the excavation to deepen the crater and, at the perimeter, to straighten the walls. All work was kept inside the boundary formed by the reinforcing bar.

Careful study of Table 3 indicates no clear relationship between the number of shots fired and the mass removed for any particular borehole. The number of shots required to break out a volume of material is more likely dependent on the geometry of the hole and interactions with cracks already formed in nearby boreholes. Shots would typically be repeated until cracks opened sufficiently to remove the material by hand or until it was apparent that the cracks would not open further.

As indicated in the remarks column of Table 3, material was sometimes dislodged during the process of drilling the holes. Where this happened, the mass dislodged was added to the total mass broken out by the HYDREX tool for that hole. In several instances, the tool was not fired in a borehole. This was usually the consequence of drilling several holes at once, then, while firing one of the holes, breaking out enough material to effectively eliminate a nearby, as yet unfired borehole.

Further remarks include mention of water leaking from borehole #18 to #13 and #17, probably along one of the extensive cracks that had been opened by then. Because of this crack system, it became difficult to create further fractures or to break out the fractured rock. An effective solution was to fire the tool, not into the boreholes but into the cracks between the boreholes. This shattered the rock locally and broke free large fragments.

The first time borehole #22 was fired, it was discovered that the HYDREX was firing feebly and not reaching pressure. It was not apparent how long this had been happening. This was indicated in the remarks column of Table 3 by "$P << 350$ MPa." The condition was corrected by repairing the discharge valve. Specific energy was calculated in an effort to compare the HYDREX tool's efficiency with other rock breaking tools. The values shown in Table 3 are cumulative values and were calculated as follows:

$$\text{S.E.} = NJ_s\rho_c/M \tag{7}$$

where N is the number of blasts, J_s is the energy per shot, ρ_c is the concrete density and M is the mass of material removed. Drilling energy is not included. The cumulative specific energy is more meaningful than individual values for each hole because of the interaction between shots. The values given in Table 3 are based on the assumption of a per shot energy of 40 kJ and a rock density of 2400 kg/m^3.

The cumulative specific energy is more meaningful than individual values for each hole because of the significant dependence between shots fired in adjacent boreholes. The specific energy values in Table 3 are initially low, indicating that the surface holes are easy to break out. However, as the excavation proceeds, the specific energy increases until it reaches an apparent steady-state value of between 37 and 40 MJ/m^3. This progression is illustrated in Figure 17. It should be noted that the addition of drilling energy in Equation (7) could easily double the calculated specific energy values. Specific energies for other rock breaking tools are shown for comparison in Figure 18.

A similar series of tests was carried out on a 1.8-m square block during testing of the prototype excavation system described in the following section. Figure 19 shows the progression of cumulative specific energy for this block. The specific energy for excavation of this block remains relatively constant for the entire test, approaching a final value of 36 MJ/m^3. This plot also shows the effect of including the energy required to drill each hole using the waterjet drill. This energy represents an additional 61 kJ per hole based on conventional drilling techniques.

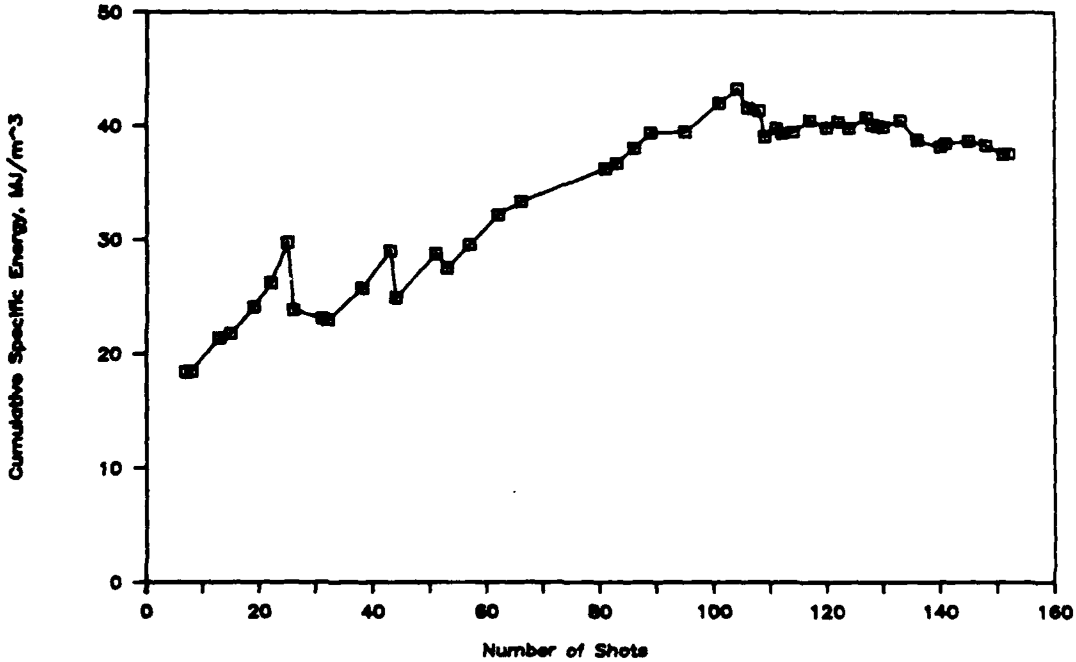


Figure 17. Cumulative Specific Energy for Excavation of Confined 1.2-meter Concrete Block

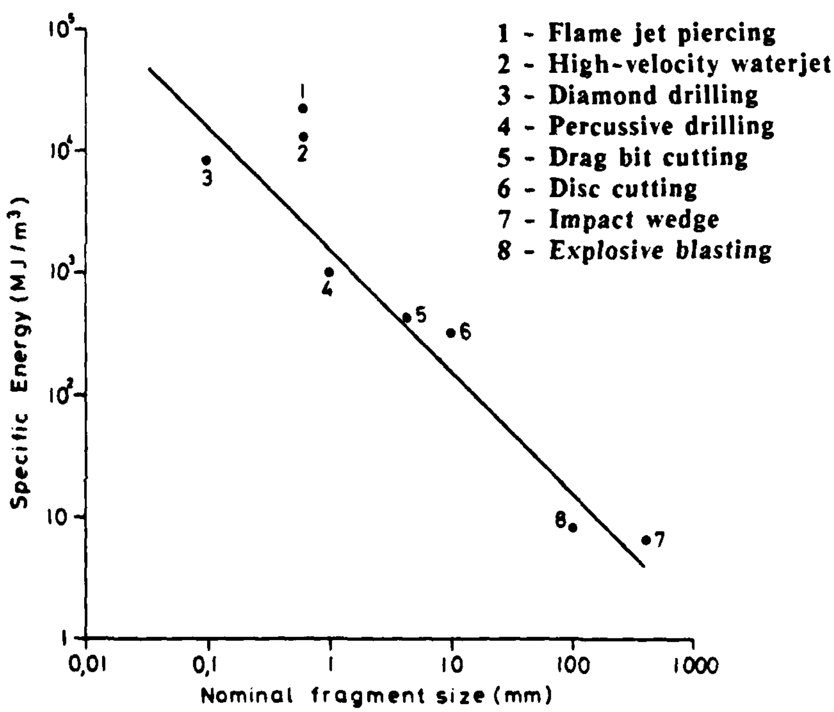


Figure 18. Specific Energy of Different Methods of Rock Breaking - Uniaxial Compressive Strength about 200 MPa (from Jaeger and Cook, 1976)

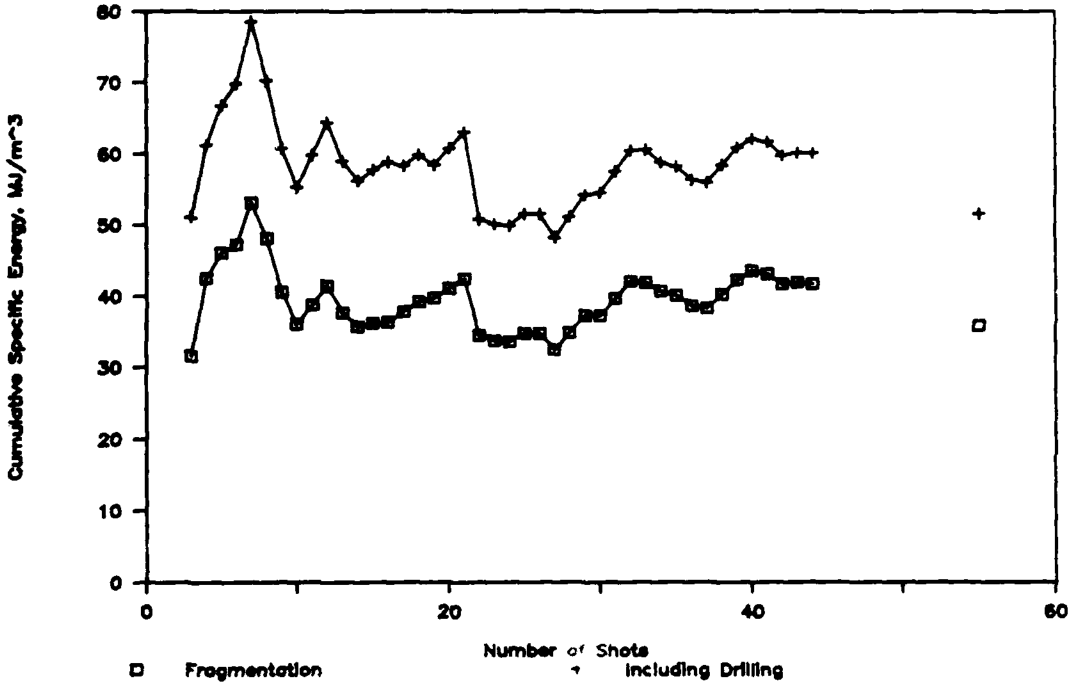


Figure 19. Cumulative Specific Energy for Excavation of Confined 1.8-meter Concrete Block

Two final observations can be made about the test results. First, when material was broken out, the exposed fractures always emanated from the very base of the borehole at the corner. This was due to a combination of the stress concentration at the corner of the drilled hole and the maximum pressure occurring at the bottom of the borehole. Second, during the course of testing, the reinforcing bar always kept fractures from opening to the external surface of the test block. Hairline fractures appeared on each of the four vertical faces, but in no case did these fractures open sufficiently for water to leak through.

As a result of these fracture tests, several conclusions can be drawn. The use of steel reinforcement in the walls and floor of the concrete block gave an acceptable method of simulating rock confinement in the laboratory. Concrete can be used as a medium for a functional simulation of rock in aspects of both drilling and fracturing with the HYDREX tool. The inclination angle of the borehole has a significant effect on the HYDREX tool's ability to remove confined rock consistently. A 45-degree angle to a flat surface is the maximum recommended for repeatable chip formation.

SECTION 5. PROTOTYPE EXCAVATION SYSTEM DESIGN

A prototype excavation system was built to evaluate the performance of the HYDREX tool in a field setting. The primary goal of the prototype design was to allow operation of the tool in a variety of orientations on a 3-m-square tunnel opening. These tests required that holes be drilled to depths of up to 200 mm and at angles of up to 45 degrees from the rock face in the vertical or horizontal plane. When drilling is complete, it is necessary to rotate the HYDREX tool into position, aligned with the hole, and to insert the tool. The system must be held steady during this process to ensure that the tool enters the hole.

The prototype excavation system design is shown in Figure 20. The HYDREX assembly is located against the rock face with a pin. Hydraulic actuators on the assembly provide two degrees of freedom in addition to the arm motions provided by the backhoe. The entire assembly can also be rotated about the locating pin axis. Drilling is accomplished with a waterjet-assisted rotary drill driven by a hydraulic cylinder and hydraulic rotation motor. When the hole is complete, the drill is withdrawn and the assembly is rotated to bring the outlet tube of the HYDREX tool in line with the borehole. The tool is inserted hydraulically and fired by venting the inlet line with a servo-valve.

5.1 Jet-Assisted Drill

A waterjet-assisted drill was chosen for the drilling operation because of its light weight and capability of drilling the 25-mm-diameter hole required for the HYDREX tool. This drill was powered by the same high-pressure pump used to charge the HYDREX tool. The drill was equipped with three 0.3-mm nozzles; at an operating pressure of 400 MPa, these nozzles deliver a power of 55 kW. Rotary power for the drill is provided with a hydraulic motor powered from the hydraulic supply for the high-pressure pump. The drill has a travel of 457 mm provided by a hydraulic cylinder.

5.2 Hydraulic Actuators

A primary consideration in the design of the hydraulic actuators was to ensure sufficient degrees of freedom of motion to allow drilling and fracturing of holes inclined at a 45-degree angle to the rock surface. Actuator motions required to achieve this

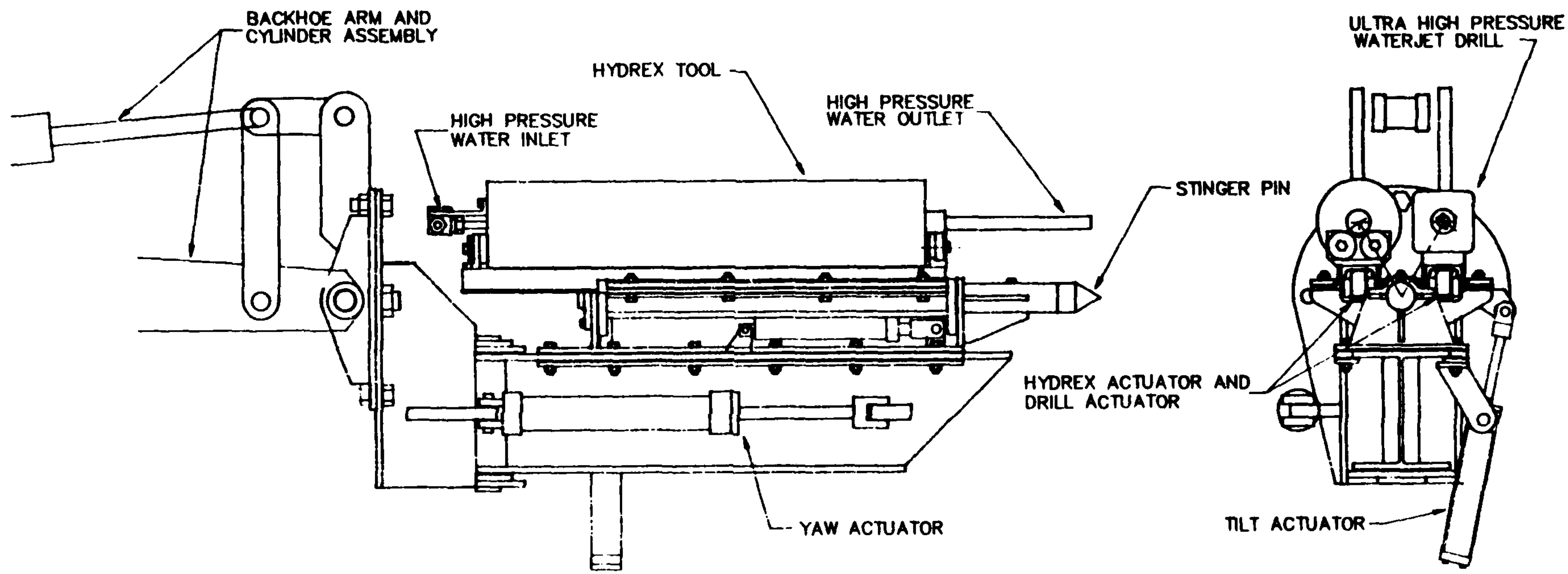


Figure 20. Prototype HYDREX Excavation System

capability were developed using a CAD system. There are five actuators mounted on the turret assembly, these include:

- o Drill feed/retract
- o Stinger extend/retract
- o Index pivot
- o HYDREX insert/retract
- o Horizontal yaw

A CAD sequence showing the operation of the tool is provided in Figure 21. Hydraulically actuated controls were also provided for turning the drill jets on and off. A flow control valve regulates the advance speed of the drill. The drill feed and turret mount assembly will work at a 45-degree angle on any surface of a 3-m-square tunnel opening as shown in Figure 22.

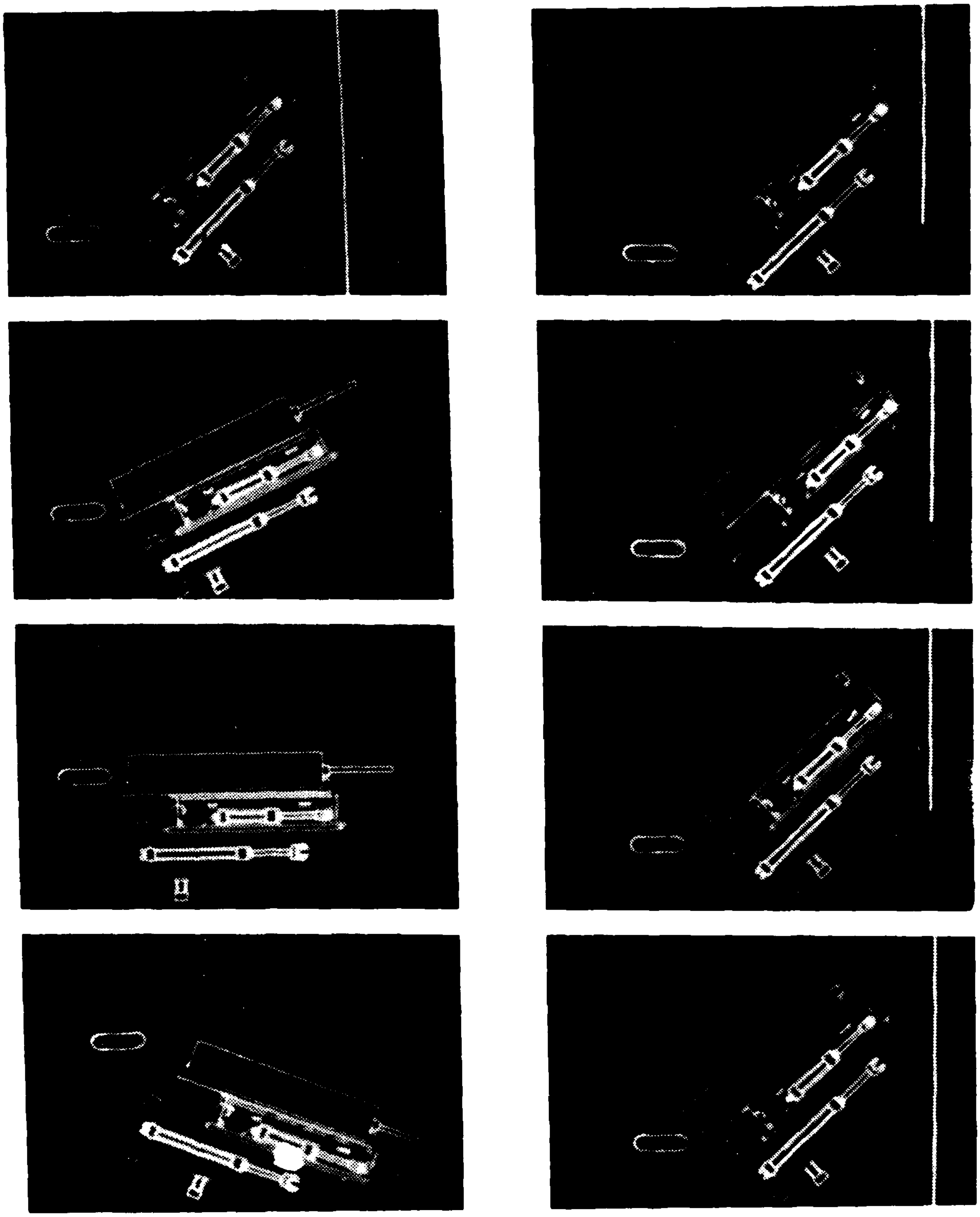
Hydraulic controls for these functions were mounted on a valve manifold as shown in Figure 23. A complete hydraulic circuit is shown in Figure 24. Hydraulic power for actuators on the turret assembly are taken from the hydraulic oil loop on the high-pressure pump.

The HYDREX tool is discharged when the vent valve, shown in Figure 25, is opened. This valve is activated by a hydraulic control line that is activated by a solenoid valve on the high-pressure pump control umbilical. Another switch on this umbilical opens the high-pressure line to charge the HYDREX tool. This umbilical also has a starter switch for the high-pressure pump and an emergency stop button that shuts the high-pressure pump down.

5.3 Auxiliary Equipment

High-pressure water for the HYDREX tool and waterjet-assisted drill is provided by an ADMAC triple-intensifier JETPAC^{TM} pump. This pump provides 0.15 liter/s of water at 414 MPa. Power is provided by a diesel engine, and the unit is field-portable.

The HYDREX turret assembly was designed to mount on the bucket link of a Case 480D backhoe. Vertical pitch motion of the turret assembly is accomplished with the bucket rotation control on the backhoe. The backhoe also provides horizontal and vertical positioning with its boom, swing and dipper controls. At its greatest horizontal extension, the boom on the backhoe has a weight capacity of 464 kg. Vertical and horizontal reach of the boom are shown in Figure 26.



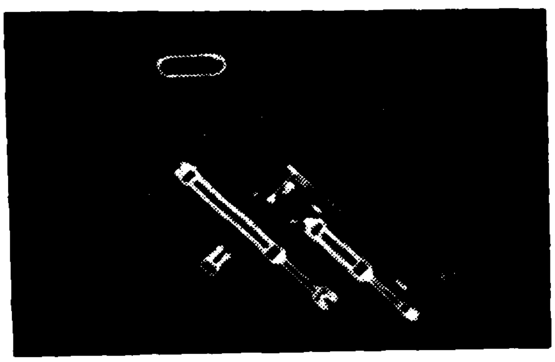


Figure 21. CAD Sequence Showing Drilling and Insertion of HYDREX Tool with Prototype Excavation System Design

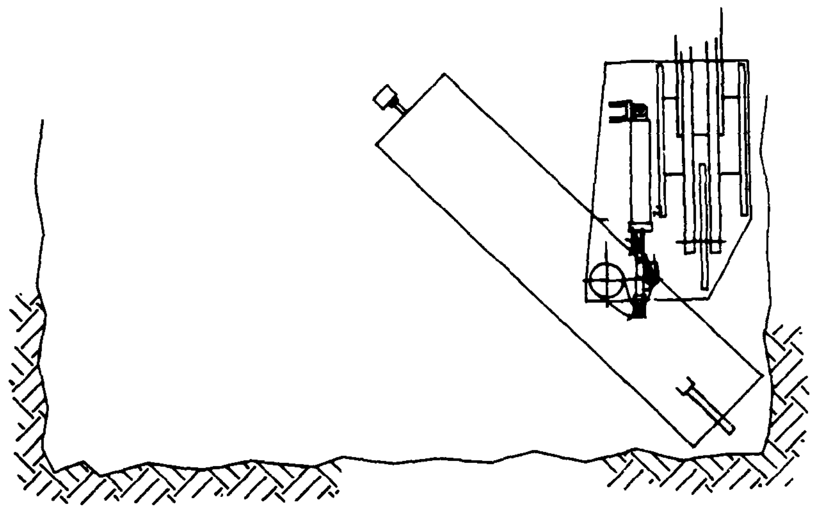


Figure 22. HYDREX Tool Orientation in a Tunnel

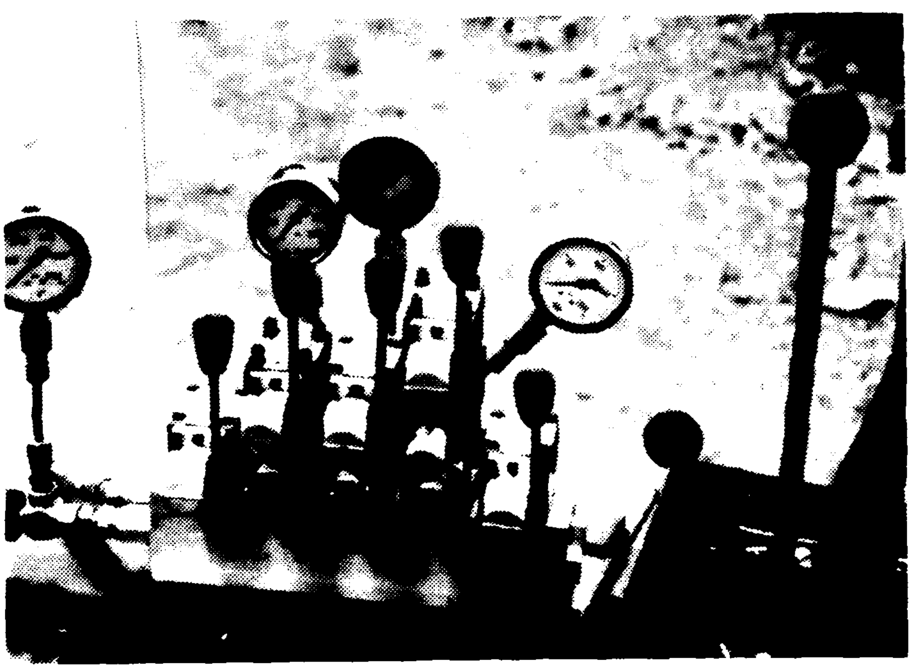


Figure 23. Hydraulic Control Valve Manifold

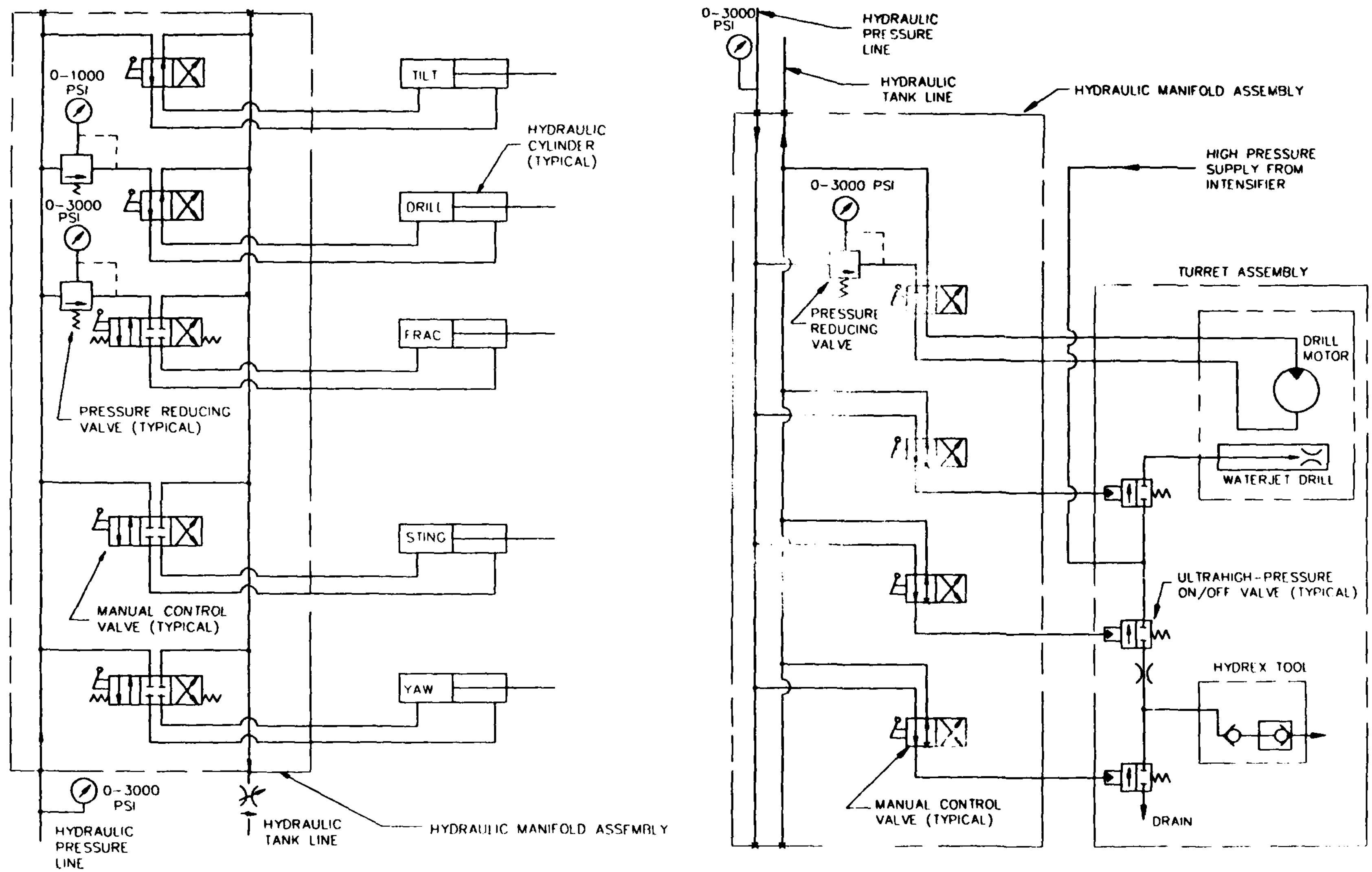


Figure 24. Hydraulic Control Circuit

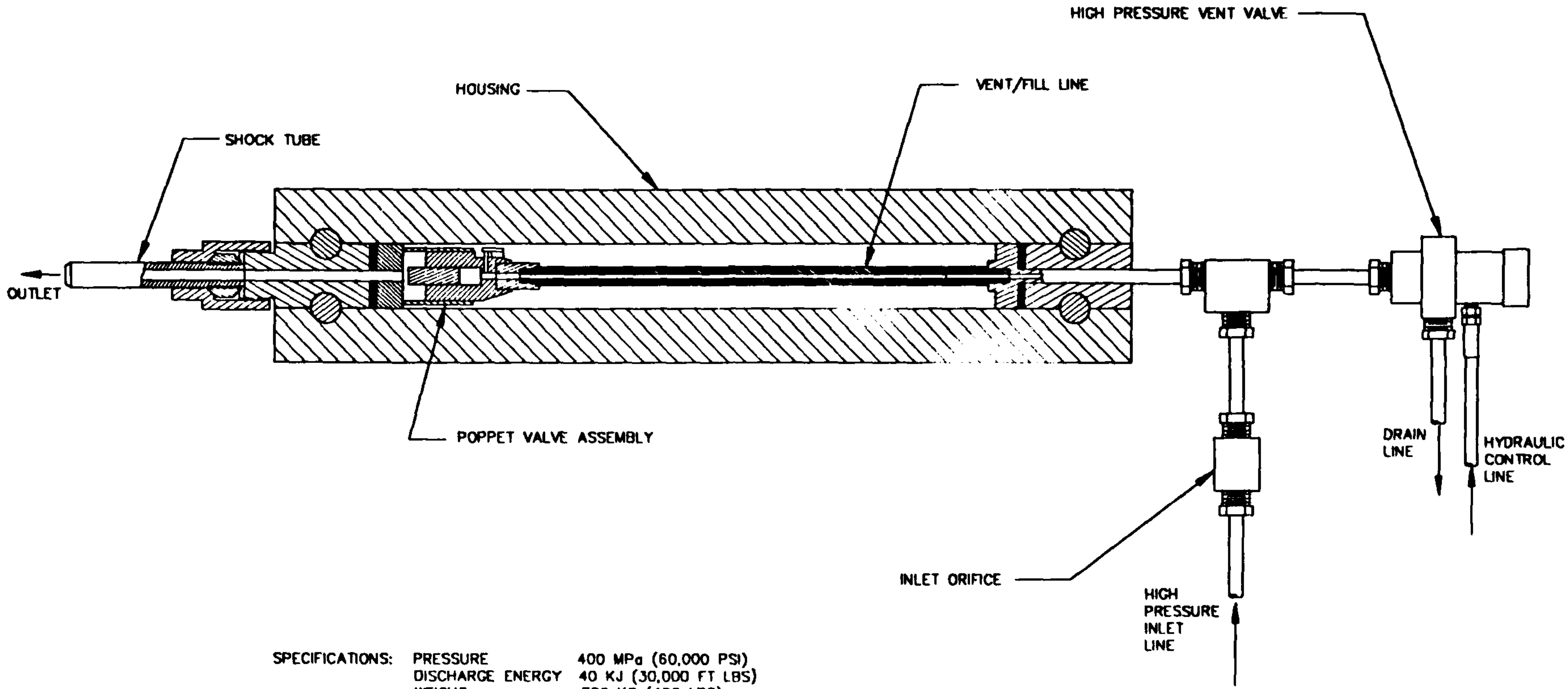


Figure 25. HYDREX Tool with High-Pressure Control Components

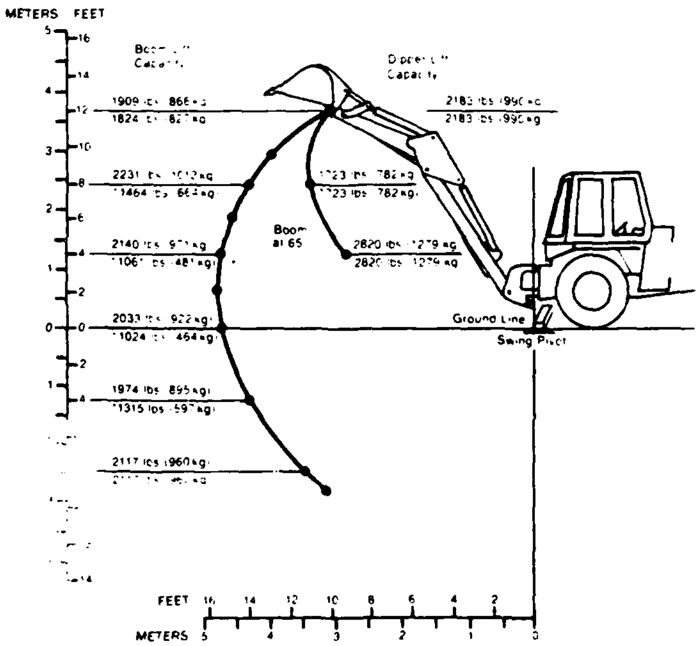


Figure 26. Case 480D Backhoe Boom Reach

5.4 Modified Inlet Stem

This valve design has now been fired over 1600 times in laboratory and field testing without failure of the poppet or significant wear. One design modification was made to increase tool safety prior to field testing. The inlet stem to the poppet valve is a single tube that leads through the end closure of the vessel down to the poppet valve assembly. If the connection between the stem and the poppet valve assembly were to fail, the stem would accelerate out the back of the tool. This design was changed so that the internal stem is larger than the inlet hole diameter. This was achieved by adding two stab seals on the vent/fill line stem inside the tool, as can be seen in Figure 25.

SECTION 6. FIELD TESTING

Field testing was carried out to determine the productivity of the prototype HYDREX system in a field setting. The system was designed for small-scale excavation of hard rock, so a test site was located in a volcanic rock quarry. A test plan was developed to meet the following objectives:

- o Excavate a tunnel entrance in confined hard rock.
- o Evaluate drill and blast pattern.
- o Determine HYDREX system productivity.
- o Determine specific energy of excavation.

6.1 Test Site

The test site was located in an andesite quarry located 2 miles west of North Bend, Washington. A 5-m-high bench was chosen for the excavation testing (Figure 27). The material was relatively massive with joints spaced about 500 mm apart. Four samples of unjointed andesite from this location were sent to a testing laboratory for compressive strength measurements (Figure 28). Three 25-mm-diameter cores were taken from each sample. The cores were cut to a length of 50 mm and ground flat to within 0.025 mm.

Figure 27. Andesite Quarry Test Location - The excavation site is in the bench to the right of the backhoe.

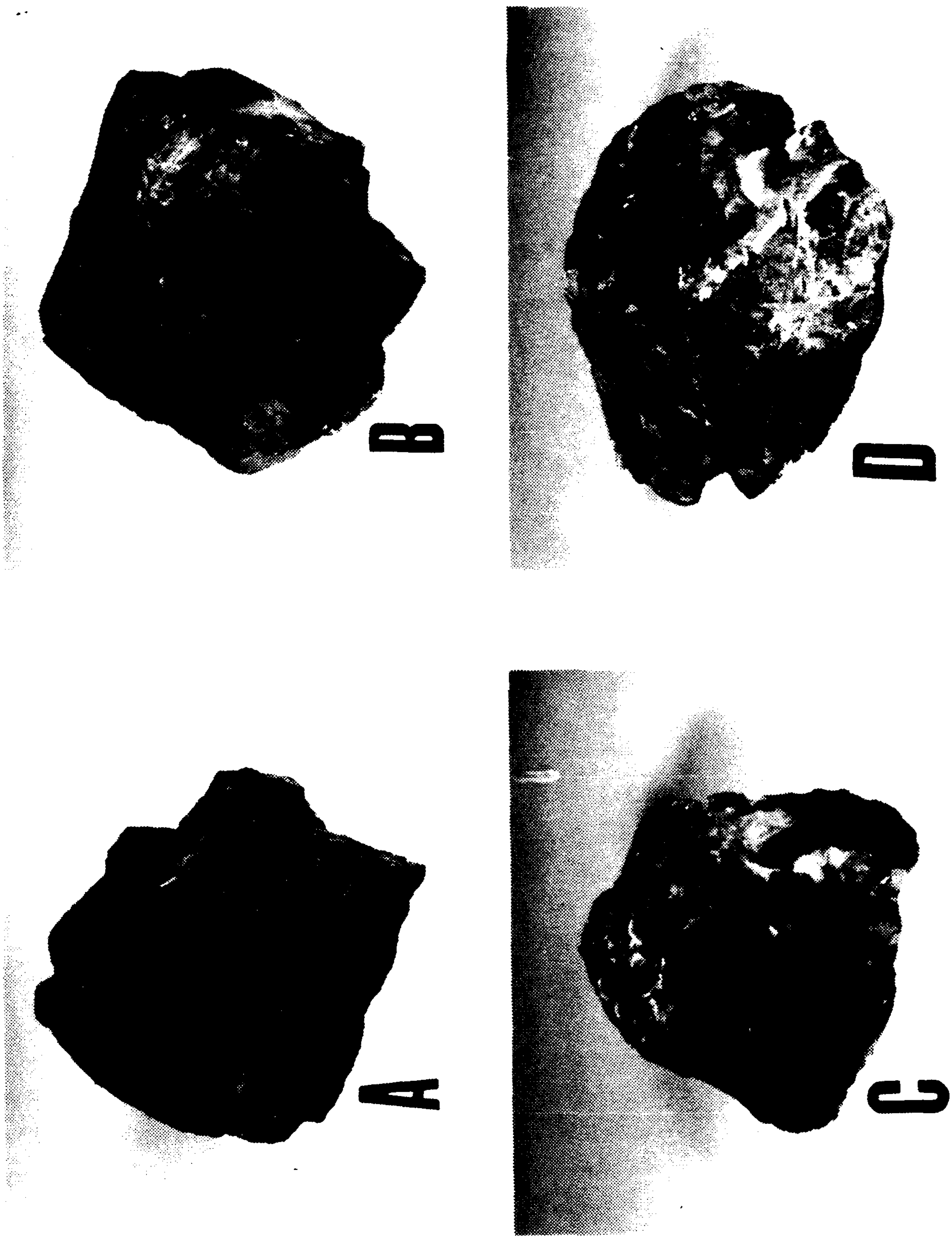


Figure 28. Andesite Samples Used for Compressive Strength Measurements

Finally, the cores were oven dried for 24 hours at 105 degrees C to remove all moisture. These cores were tested for unconfined compressive strength according to the ASTM D-2938 standard. The results are given in Table 4. The compressive strengths for the samples cover a considerable range: from 74 to 263 MPa. The two lower-strength samples, C and D, were lighter colored than samples A and B. The lighter-colored material was located in the lower half of the excavation, and the stronger, darker material was in the upper half.

Table 4. Unconfined Compressive Strength of Andesite Samples

Sample-Core	Strength (MPa)
A-1	188
A-2	263
A-3	265
B-1	158
B-2	177
B-3	214
C-1	99
C-2	151
C-3	149
D-1	74
D-2	89
D-3	86

6.2 Drilling Tests

The initial test period was devoted to determining the drilling characteristics of the waterjet-assisted drill in the andesite. The drill was designed to drill a 23.8-mm hole; however, a larger-diameter cap was installed to allow drilling of 25.4-mm holes. The cap was produced by brazing a larger-diameter carbide cross bar to a regular size cap.

Tests were carried out with three drill cap sizes: 23.8, 25.4 and 27.0 mm. A set of cylindrical hole gauges was used to determine the size of tube that the drilled hole would accept. The results are given in Table 5. The larger cap sizes drilled larger holes, but the holes were not straight or round and the size of tube that would fit into the holes was actually smaller than the cap size. Only the 23.8-mm cap drilled a straight, round hole that would accept a 23.8-mm tube. The larger cap sizes were also susceptible to failure of the more exposed carbide bar.

Table 5. Waterjet-Assisted Drilling Tests

Cap Size (mm)	23.8	25.4	27.0
Hole Diameter (mm)	23.8	25.0	25.5

As a result of these tests, the discharge tube on the HYDREX tool was turned down to an outside diameter of 23.8 mm. The 23.8-mm drill caps were then used for all of the excavation drilling. The drilling was carried out at 380 MPa and a flow rate of 0.24 liter/s for a power of 92 kW.

6.3 Excavation Plan

In the concrete block testing it was learned that the most efficient excavation technique requires that the blast hole be oriented as close to parallel to a free surface as possible. Our original plan called for a spiral blast pattern in which each shot is a bench shot as illustrated in Figure 29. The peak pressures developed by the HYDREX are concentrated on the hole bottom, like the concentrated charge used in bench blasting (Johansson and Persson, 1970). The pressures required to drive radial cracks from the upper portion of the hole to the bench face are much lower and must be provided by the pressure drop in the annulus between the hole and the discharge tube.

In practice, it was not possible to obtain all of the tool orientations required to initiate a spiral blast pattern. Instead, a more conventional technique was used to develop a free face for blasting.

The excavation plan is illustrated in Figure 30. The initial series of shots is fired perpendicular to the rock face to define the perimeter of the hole. This is similar in concept to smooth-wall blasting where a series of low-velocity charges are detonated around the perimeter of a tunnel opening prior to the main blast sequence. The perimeter shots generate radial fractures that tend to link up with each other. These fractures prevent damage to the excavation wall from later shots.

The second series of shots illustrated in Figure 30 is designed to produce a central cavity similar in concept to the "burn" hole produced by the initial charges in a conventional blast design. These shots must be inclined at a high angle in order to be effective. Once the initial opening is produced, a series of shots is fired surrounding the initial opening but at a lower angle to deepen the central cavity to 150 mm. Successive shots are essentially bench shots with a drilled hole perpendicular to the rock face. The number of shot sequences required to reach the tunnel perimeter depends on the rock

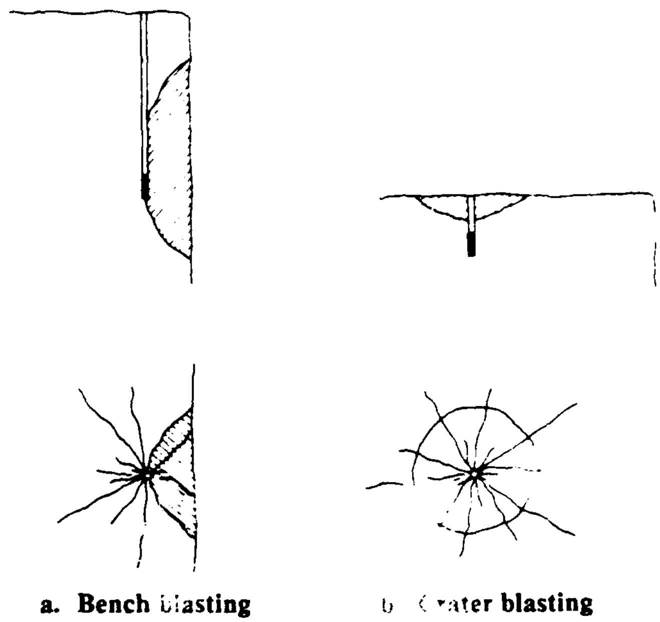


Figure 29. Comparison Between Bench Blasting and Crater Blasting (from Johansson and Persson, 1970)

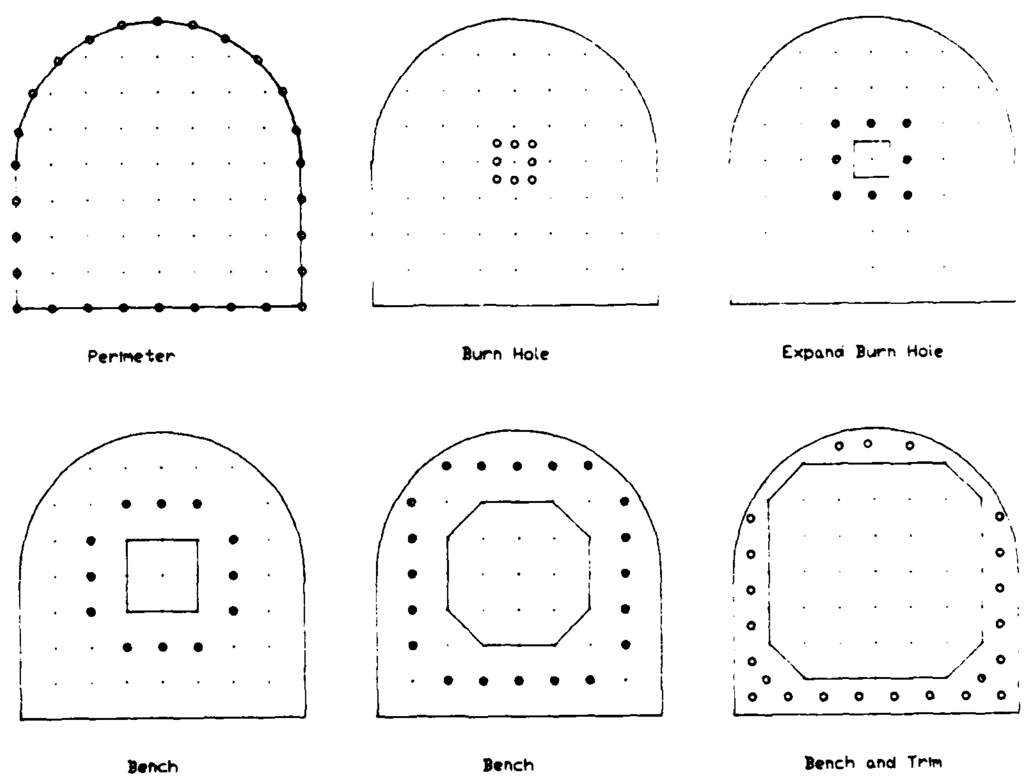


Figure 30. Excavation Plan

removed per shot. The final series of shots was designed to trim the material from the excavation corners.

6.4 Productivity

Productivity and energy efficiency were obtained by excavating the tunnel opening shown in Figure 31. A horseshoe-shaped tunnel opening 8 feet (2.4 m) high was marked off with a 1-foot grid spacing. The surface area of the opening was 5.3 m^2. Excavation was carried out over a period of 8 days as outlined in Table 6. Maintenance and data-logging limited excavation work to a few hours each day. During these periods, excavation was carried out continuously with a crew of two. One person operated the HYDREX system from the backhoe cabin, and the other guided tool placement and drilling, cleared the face of loose rock and maintained sufficient room for the tool to maneuver near [illegible] of the excavation. Scaling and mucking were carried out by hand with the aid of a scaling bar.

Table 6. Field Test Productivity

Date mm/dd	Time hr:min	# Holes	# Shots	Removed Wt. (kg)	Volume (m^3)	S.E. (MJ/m^3)
6/23	2:30	9	60	900	0.33	7.6
6/24	2:45	14	40	0	--	--
6/27	2:00	12	89	800	0.30	12.5
6/28	1:30	9	42	650	0.24	7.4
7/1	3:45	14	130	1200	0.44	12.4
7/5	2:45	10	68	800	0.29	9.8
7/6	3:45	16	75	1550	0.56	5.6
7/7	4:30	15	122	950	0.35	14.6
Total	23:30	99	681	6850	2.51	11.4

A record was maintained of excavation time, number of holes drilled and number of tool firings. The excavation process was also recorded on videotape. At the end of each day the muck pile was weighed. A summary of these test results is contained in Table 6. Each hole was fired an average of three times. After three blasts, additional blasts did not appear to enhance fragmentation. The tool was also fired an average of four times outside of the holes for each hole drilled. These shots were useful for extending existing fractures and to assist in scaling partially loosened rock from the surface.

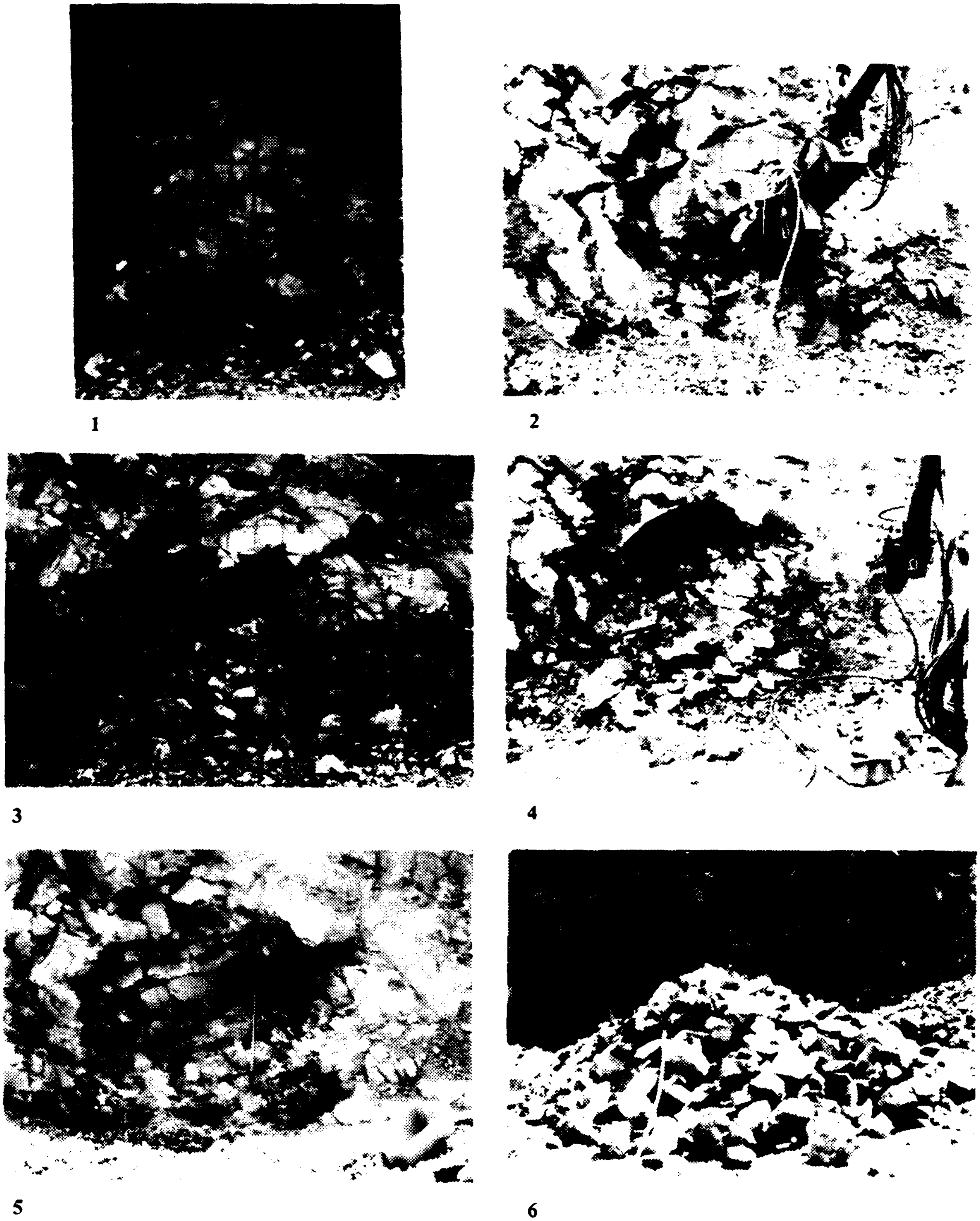


Figure 31. Tunnel Excavation Sequence

The specific energy of excavation in Table 6 is calculated assuming a discharge pulse energy of 42 kJ. The drilling energy is not included in this calculation. Each 150-mm hole required between 30 and 60 seconds to drill depending on the rock hardness. Assuming an average time of 45 seconds per hole, this is an energy expenditure of 4.1 MJ per hole. The specific energy associated with drilling is 232 MJ/m^3, which is an order of magnitude greater than the energy associated with the blast. The waterjet-assisted drill is very inefficient when compared to conventional hydraulic drills. Referring to Figure 18, we see that the specific energy for conventional drilling of hard rock (200 MPa) is only 1000 MJ/m^3, which translates to 74 kJ per hole or an additional specific energy that would be associated with conventional hydraulic drilling of only 4.1 MJ/m^3.

The rock face was inclined slightly from the vertical with a bench along the foot of the face. The first day of excavation (6/23) was spent removing this bench. The perimeter shots were fired on the second day (6/24) with essentially no rock removal as indicated in Table 6. No perimeter shots were fired along the foot of the excavation because it was not possible to drill a hole perpendicular to the face at this location. To drill and blast these holes, it would have been necessary to rotate the entire assembly 180 degrees. The turret mount was designed to allow manual rotation of the tool; however, this would have required working underneath the boom of the backhoe while it was extended, which is not considered a safe procedure.

The third day (6/27) was spent in generating the "burn" hole at the center of the excavation as illustrated in the second and third steps of the drilling plan. This day represents the highest specific energy of excavation observed during the test. The high specific energy is due to the difficulty in removing rock when there is no bench face available. These holes were drilled at 45 degrees to the rock face, and several were required to initiate the burn hole.

The following two days (6/28 and 7/1) were spent in bench blasting to the perimeter of the hole. The pattern of rock removal was strongly controlled by the joint pattern in the rock. Shots fired into joints were ineffective compared to shots in holes drilled into competent rock. The joints also defined the limits of the rock removed as can be seen in Figure 31. Joint surfaces parallel to the rock face aided in fragmentation. Joints normal to the rock face could aid or hinder excavation depending on whether the joints converged or diverged. Diverging joints tended to hold the fragmented rock in place. This excavation sequence removed a layer of rock approximately 250 mm thick from the rock face.

On the 6th day (7/5) another burn hole was initiated in the center of the face. This hole was extended to the perimeter of the opening on the following two days (7/6 and 7/7). The second excavation sequence extended the tunnel to a total depth of 500 mm as seen in Figure 31. Further excavation was not carried out because of the hazard of hand scaling and mucking underneath an overhanging tunnel entrance.

Total productivity during the excavation was 2.5 m^3 in 23 hours and 30 minutes. In retrospect, it appears that the initial perimeter shots did not contribute significantly to the wall smoothness and could have been avoided. Further improvements in the system design that will significantly improve this productivity are identified in the section on Commercial System Design (Section 7). The specific energy for fragmentation compares favorably with the values for explosive blasting given in Figure 18.

6.5 Operations and Maintenance

A number of equipment failures occurred, as is expected in the course of field testing any new prototype system. These are listed in Table 7. Most of these failures are due to operation at high pressure. As discussed in the commercial system design, it is possible to operate the HYDREX effectively at 300 MPa where equipment fatigue and failure will occur at a much lower rate. The inlet orifice also contributed to some of the problems. This is a 0.5-mm carbide orifice installed in the HYDREX charge line to prevent pump overstroking during the low-pressure portion of the charge cycle. This orifice will be eliminated in the commercial design.

Table 7. Equipment Failures

Item	Description / Repair
Drill advance	Advance ram attach point cracked / Welded reinforcement plate
Drill stem	High-pressure leak due to wear and fatigue / Remachined past leak
High-pressure hose	11 hose failures at 380 MPa in surplus hose supplied by hose lab / Replace
Vent valve	10 failures due to erosion of poppet seat / Rebuild
Inlet orifice	Carbide orifice worn / Replace
Inlet check valve	Retainer screw cracked / Replace
Inner stem	6 stab seal failures / Rebuild with spacers to limit backup tube travel
Swivel	Seal failure / Rebuild

SECTION 7. COMMERCIAL SYSTEM DESIGN

The field tests with the HYDREX excavation system showed that the primary difficulty faced in obtaining good excavation results with a water pulse tool is not generating fractures but propagating large fractures, portions of which may have intersected a free surface allowing the pressure to vent. This was also demonstrated during our field tests with ADMAC's FLOWEX™ tool (Kolle, 1986).

The FLOWEX generated significant volumes of water at relatively low pressures. The pressure due to flow from an orifice into the gap between the two surfaces decays rapidly with radius as shown in Figure 32. The resulting load distribution is concentrated at the region near the orifice, which limits the stress at the crack tip. In the case of the FLOWEX tool, the load induced by pressure drop through vented cracks was not sufficient to complete the cracks.

The flow rates induced by the prototype HYDREX tool are much higher and the induced pressure drops are 10 to 20 times higher than for the FLOWEX; however, the discharge volume of the prototype tool is very small. In most of our testing with this tool, it was discharged, with a valve, into a dry hole. This means that the discharged volume must fill the discharge tube, the borehole cavity and the initial portion of the fracture before any crack extension loads are applied. We have found that the tool needs to be bottomed against the hole bottom for good fracturing in a dry hole. It is also difficult to propagate vented fractures that are not full of water with the prototype tool. We have considered precharging the holes with water to increase the loading on vented fractures, but this has not been tried yet in the field.

7.1 HYDREX Tool

The results of our field testing and analysis indicate design changes that should improve the performance of the HYDREX tool. We have developed a model that provides the pressure pulse profile from a given HYDREX tool configuration. The pressure profile is a function of the vessel pressure, internal volume, outlet diameter and vent area. Figure 33 shows the variation in stored energy of tools with various pressure ratings but with the same outside diameter. There is a maximum in stored energy at 300 MPa. This is a consequence of the decreasing compressibility of water at high pressures and increasing thickness of the pressure vessel walls.

The pressures acting to open a vented fracture are greatest when the peak flow rate is greatest. This can be achieved at lower operating pressures with a larger-

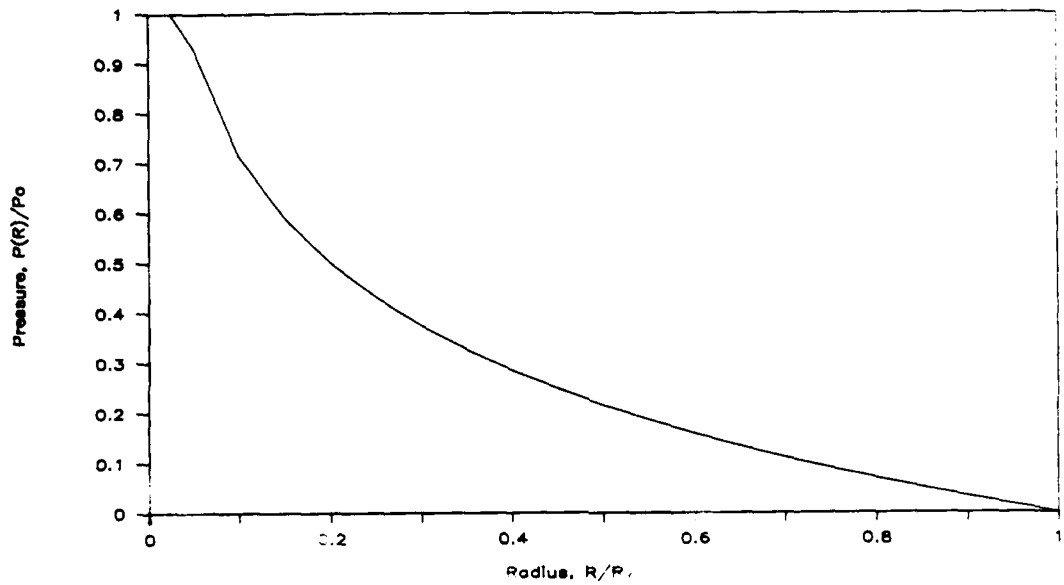


Figure 32. Radial Decay of Pressure in the Aperture Between Two Parallel Plates

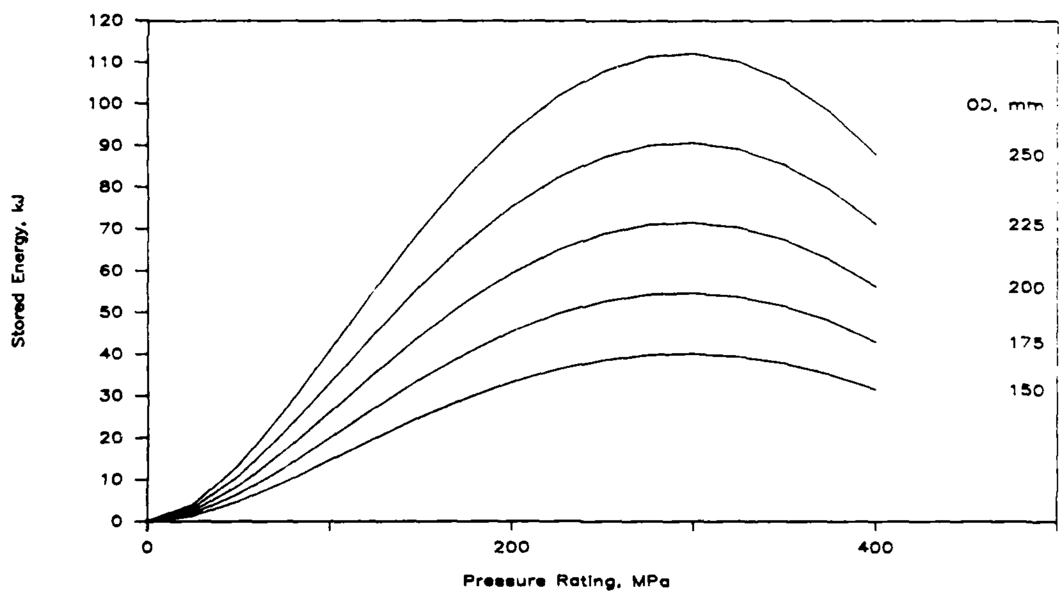


Figure 33. Variation of Stored Energy with Pressure Rating of a HYDREX Tool with Fixed Outside Diameter and Length

diameter outlet tube and a larger discharge valve. We estimate that the operating pressure should be reduced to 300 MPa and the valve outlet diameter increased to over 25 mm. Specific design recommendations for a commercial HYDREX tool are summarized in Table 8.

Table 8. Proposed HYDREX Tool Specifications

Operating Pressure	300 MPa
Length	1800 mm
Diameter	180 mm
Internal Volume	10 liters
Discharge Volume	1 liter
Stored Energy	130 kJ
Outlet Diameter	25 mm
Borehole Diameter	40 mm
Initial Flow Rate	285 liters/s
Mass	250 kg

The operating pressure should be reduced to around 300 MPa to allow reliable operation of all components and to increase the discharge pulse power. The peak borehole pressures developed at this pressure will still be well in excess of the tensile strength of any rock type and should be capable of inducing multiple fracturing. The stored energy will also be a maximum at this pressure for a given tool length and external diameter. Our testing and modeling of the 400-MPa HYDREX tool have shown that the discharge volumes and flow rates at this pressure are too low for effective pressurization of vented fractures. The reliability of the valve system components will also be much better at 300 MPa.

The internal volume of the tool will be significantly higher than the 400-MPa HYDREX. The commercial tool would have a 180-mm OD with an internal volume of 10 liters. This tool will be about twice as long as the present configuration. At the maximum rated pressure of 300 MPa, the discharge volume will be 1.0 liters with a total stored energy of 130 kJ.

The lower pressures and increased volume of the tool are consistent with a larger hole diameter. Commonly available hydraulic drifters will drill a hole with a diameter of 40 to 42 mm. The commercial tool would have a 35-mm diameter discharge nozzle with a 25-mm bore. This gives an annular clearance of 2.5 mm in a 40-mm hole. The

The length of the nozzle should not affect dynamic pressures in the bottom of the hole. The very high pressures observed on the hole bottom are due to the high fluid velocity, not friction between the nozzle and rock. Even at these high velocities, the pressure drop through a long discharge nozzle is negligible compared to the dynamic pressures.

The peak pressures observed in the hole are due to stagnation of the high-velocity flow on the borehole walls. These pressures will not be affected by improving the annular clearance fit or sealing the hole. Calculated pressure drops due to friction in a 2.5-mm annulus are very small. Secondary extension of vented fractures may benefit from a taper seal at the hole entrance. To provide better sealing of secondary pressures, the commercial tool should be provided with a taper seal as shown in Figure 34.

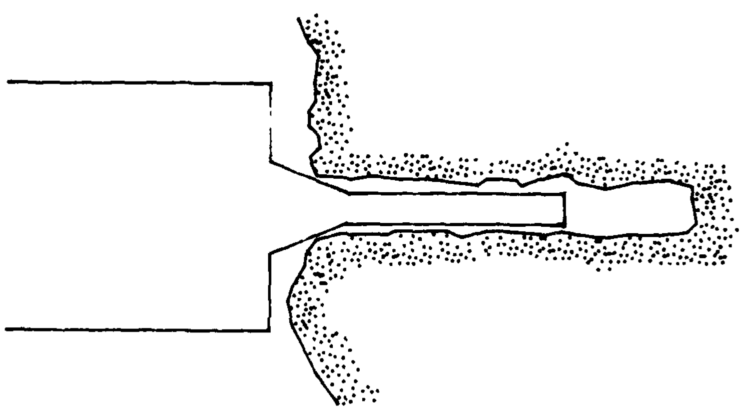


Figure 34. Taper Seal Arrangement for Proposed HYDREX Tool

The internal components of our present pilot-operated poppet valve design have been very reliable at 400 MPa. After 1000 firings of this valve, we see no signs of damage. We propose to scale this valve design up from 11 to 25 mm.

We have been using ADMAC's 280-MPa valve for the external vent line. This valve is not reliable at the higher pressure but should operate at 300 MPa without problems. All other components of the system, including pumps, hoses and swivels, will be much more reliable at 300 MPa.

We believe it will be beneficial to prefill fractured holes to provide maximum secondary fracturing. A low-pressure pump will be provided for prefilling through a check valve in the discharge nozzle body.

7.2 Excavation System

The backhoe mount used in our field tests did not provide the maneuverability and stability required for rapid excavation. A commercial system should be mounted on a mining vehicle such as the single-boom jumbo shown in Figure 35. A typical jumbo will have an electric hydraulic motor powered by an electrical umbilical. This power unit would be used to power a high-pressure intensifier integral to the jumbo. These jumbos are already equipped with a highly maneuverable rollover boom to allow drilling at any location on the rock face. The HYDREX tool will be mounted parallel to an existing hydraulic drifter. The rollover control on this boom will provide the indexing required for tool insertion. Figure 36 shows the HYDREX system schematic for a single-boom jumbo.

7.3 Productivity Improvements

Field testing was carried out for 23.5 hours in a volcanic rock quarry. During this time, the HYDREX tool was fired 681 times and 99 holes were drilled. A two-person crew removed 2.51 m^3 of rock in this time, which converts to 2.56 m^3 per day or 0.025 m^3 per hole. In the following, the time spent per hole is broken down by activity:

Tool positioning:	329 seconds
Drilling time:	45 seconds
Index/insert:	6 seconds
Charge time:	70 seconds
Mucking:	400 seconds
	850 seconds

The field tests resulted in a number of design changes that will substantially improve performance of a commercial HYDREX system. Mucking, tool positioning and charge times will all be reduced by the following modifications to the system:

- Conventional hydraulic drill
- Increase drill/insert stroke
- 360-degree, compact rotary actuator
- Mechanized mucking
- Automatic valve shutoff

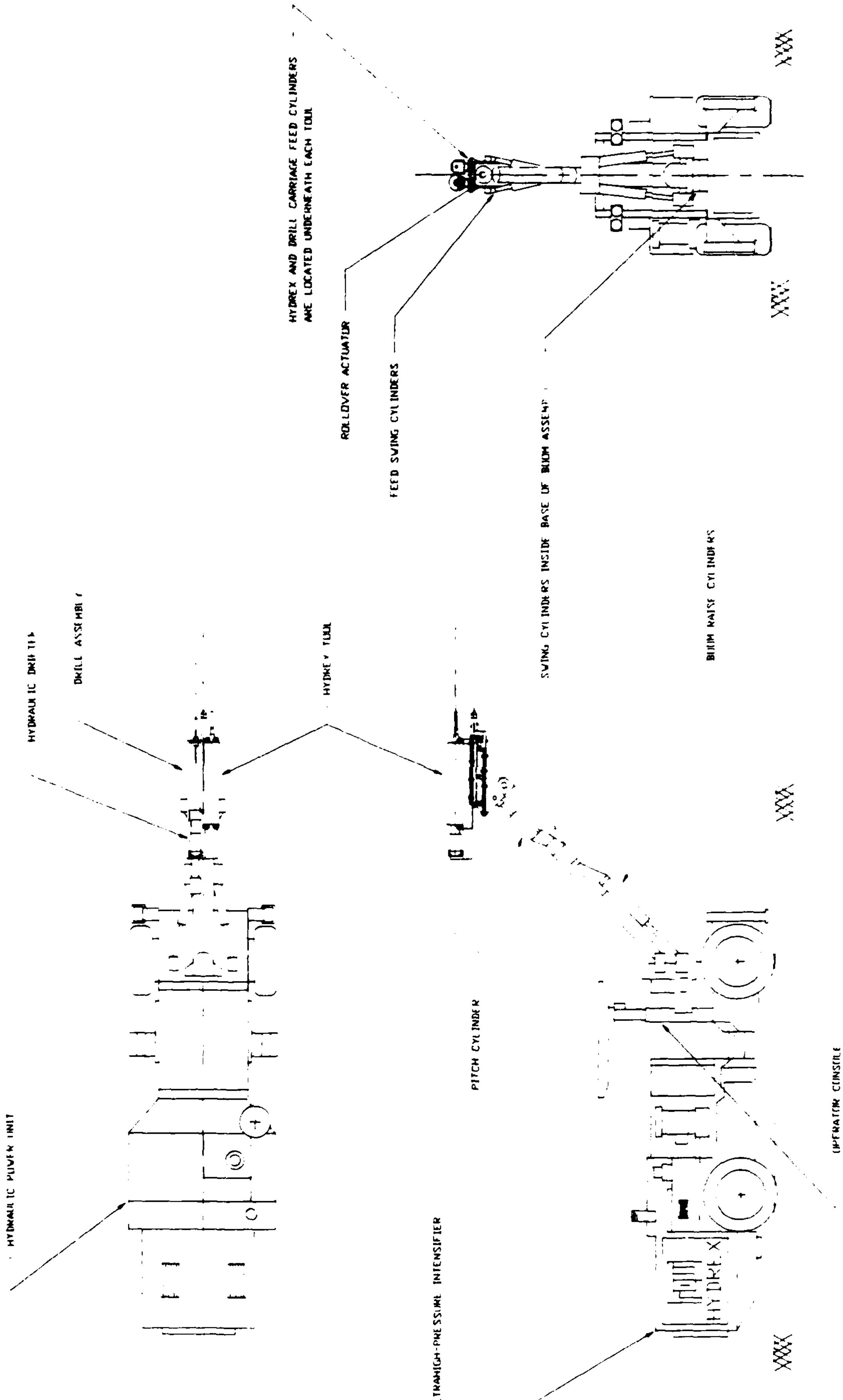


Figure 35. HYDREX Tool Mounted on a Single-Boom Jumbo

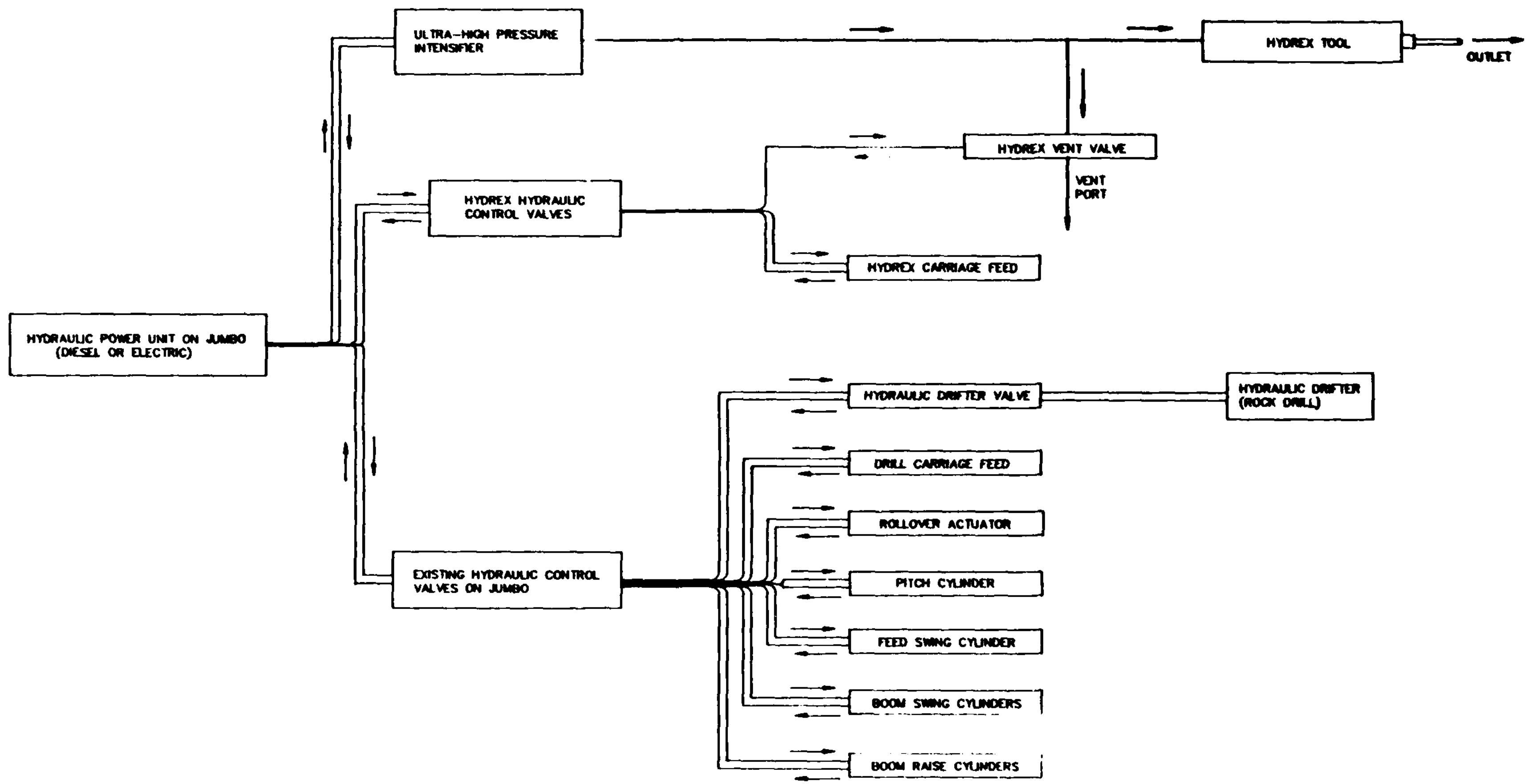


Figure 36. Control Schematic for Commercial HYDREX System

The following activity breakdown is based on these improvements:

Tool positioning:	60 seconds
Drilling time:	60 seconds
Index/insert:	6 seconds
Charge time:	14 seconds
Mucking:	60 seconds
	200 seconds

This should increase the number of holes drilled to 432 per day. Productivity per shot should also be substantially improved by increasing the discharge volume from 0.25 to 2.0 liters. Assuming this will increase productivity proportionally per hole to 0.200 m^3 gives a potential excavation rate of 86 m^3 per day in confined hard rock.

A preliminary design has been prepared for a HYDREX system kit that could be added to a conventional single-boom drilling jumbo in one day at the job site. A small drilling jumbo equipped with a mucking loader should cost about $250,000. The estimated cost for a HYDREX system kit that includes a HYDREX tool, manipulator, drill and high-pressure pump is less than $100,000. We estimate daily costs for a fully utilized system will be:

HYDREX kit:	$150
Single-Boom Jumbo	$375
Labor (3 people @ $24/hr ea.):	$1728
Expendables:	$100
	$2353

The prototype and potential performance of this system are compared with conventional techniques in Table 9. This comparison shows that the HYDREX system operating costs are comparable to conventional tunneling systems for large projects. The system described here is appropriate for smaller projects requiring a highly flexible system with minimal setup time.

This productivity may be compared with a tunnel boring machine and conventional blasting using a large jumbo. A cost and productivity comparison is provided in Table 9. Conventional tunneling cost and production estimates are based on a 10-m^2 tunnel excavation with a total length of 10 km (O'Hanlon and Kolle, 1986). Drill and blast costs are based on a four-boom jumbo with a 13-person crew. The

tunnel boring machine costs are based on a 3.7-m-diameter machine with a 7-person crew. This comparison does not include the cost of a concrete liner, which will tend to increase the total cost of a tunnel built using the HYDREX system or conventional drill and blast techniques.

Table 9. Performance Comparison

	Cost per m^3	Production (m^3/day)	Production (m^3/person-day)
Prototype HYDREX System	$222	2.5	1.25
Commercial HYDREX System	$40	84	28
Drill and Blast	$105	422	32
Tunnel Boring Machine	$73	211	30

SECTION 8. CONCLUSIONS

The development of secure underground facilities for defense systems requires new techniques of excavating hard rock that overcome the limitations associated with the use of explosives or tunnel boring machines. Explosives are an efficient way of excavating hard rock; however, conventional drill and blast methods may pose a hazard to nearby facilities or personnel through fly rock, dust generation, excessive ground motion and release of toxic fumes. Blasting is thus limited to remote tunnels and mines where these factors are less important. Blasting also introduces significant damage to the walls of a tunnel so that concrete liner must often be placed to prevent rockfall.

Another rapid excavation technique uses tunnel boring machines (TBMs). These are large, expensive machines requiring significant time for site preparation, assembly and breakdown. They provide cost-effective nonexplosive excavation of long tunnels where the high capital cost and long setup/breakdown times are offset by the advantages of continuous tunneling and a smooth circular tunnel profile, often requiring no liner. TBMs are inappropriate in short tunnels or in situations where a noncircular or nonstraight geometry is required.

The hydraulic excavation (HYDREX) system developed during this SBIR project is capable of nonexplosive excavation of hard rock in any geometry required. The objective of the Phase II project was to develop the HYDREX concept into a practical excavation system.

The first task of this project was to develop a quick-opening discharge valve for the HYDREX tool, since the use of rupture disks was considered impractical. This work resulted in a poppet valve design with discharge characteristics superior to the burst disk. This valve allows the tool to be repeatedly discharged, greatly improving productivity. The prototype HYDREX tool developed in Phase II delivers a hydraulic impact comparable to the most powerful impact hammers available.

Excavation of reinforced concrete blocks was carried out with the prototype HYDREX excavation system to evaluate fragmentation and productivity in confined material. The specific energy required for excavation of the concrete was measured and found to be similar to that of conventional drill and blast techniques and substantially lower than required by a tunnel boring machine.

In addition to being relatively efficient, a practical excavation system must be extremely reliable. During testing, the prototype HYDREX tool was fired over 1650 times without wear of critical valve parts.

Field testing of the prototype HYDREX system was carried out in a hard volcanic rock quarry. The system was used to excavate a horseshoe-shaped tunnel opening into an andesite face. These field tests provided estimates of tool productivity and resulted in the design of a practical hydraulic excavation system with a variety of applications. The capital cost of the equipment is low compared to tunnel boring machines, and the system may be quickly deployed to meet the needs of a complex tunneling or construction project.

Air Force applications for the HYDREX system include construction or expansion of hardened ballistic missile launch sites and command centers. The greatest application will be for moderate-sized openings where conventional blasting is not an option and tunnel boring machines are too expensive. The flexibility of the HYDREX system will greatly reduce the cost of moderate-sized facilities in hard rock, thereby expanding the range of options available to Air Force planners.

A number of commercial applications for the HYDREX tool have also been identified, including deep-level nonexplosive mining, urban construction, concrete demolition and boulder fragmentation. The use of this flexible, nonexplosive excavation system will substantially reduce the cost of these types of projects.

A highly specialized application of the HYDREX tool has already been realized. A modified version of the tool is now being tested by the operator of the Three Mile Island nuclear power plant as a means of fragmenting the melt products pooled in the bottom of the reactor vessel. Fragmentation tests on hard materials thought to characterize this material have been highly successful.

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APPENDIX A

EQUIPMENT SPECIFICATIONS

case

480D Construction King®

47 (35 kW) NET FLYWHEEL HORSEPOWER
Case-built four cylinder 188 in³ (3081 cm³) high torque diesel.

FIELD PROVEN SYNCHRONIZED TRANSMISSION
Four speed with full power shuttle and torque converter.

CHOICE OF BACKHOES
12′ (3.66 m) Backhoe or 12′-15′ (3.66 m - 4.57 m) telescoping Extendahoe®. Over-center backhoe transport position for loading and roading stability.

3000 LB (1361 kg) LIFT CAPACITY LOADER
Dual lever controls, in line loader linkage with 5,700 lb (25 355 N) breakout.

UNITIZED MAINFRAME
Absorbs heavy shock loads, maintains power train alignment, simplifies servicing.

COMPONENTIZED POWER TRAIN
Permits servicing of individual components without disturbing the rest of the drive line.

OPERATOR CONVENIENCE
Roomy work platform, sloping hood and grille improves visibility and operator efficiency.

Unit shown is equipped with non-standard items

J I Case
A Tenneco Company
700 State Street Racine, WI 53404 U.S.A.

TENNECO

Specifications 480D Tractor Construction King®

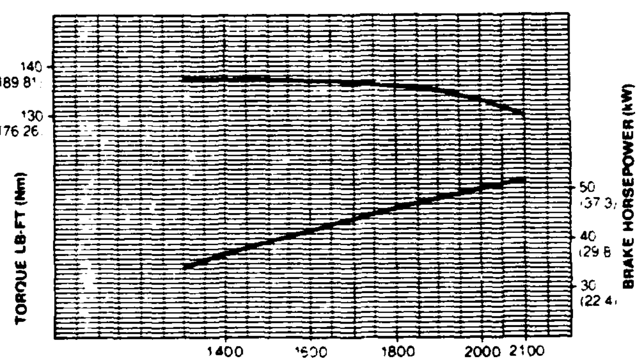
ENGINE

Make and model	Case G188D diesel
Type of fuel	No. 2 diesel
No. of cylinders	4
Bore and stroke	3.812" x 4.125" (97 mm x 105 mm)
Displacement	188 in^3 (3081 cm^3)
Compression ratio	17.5 to 1
Fuel induction	Injectors
Fuel supply	Injection pump
Air cleaner	Dry type, replaceable cartridge
Oil filter	Full flow, replaceable spin-on cartridge
Lubrication	Positive pressure
Cooling system	Pressurized—7 psi (48 kPa)
Horsepower	
Gross (1)	52 @ 2100 rpm (39 kW @ 2100 r/min)
SAE Net (2)	47 @ 2100 rpm (35 kW @ 2100 r/min)
Max. torque ft-lb	
Gross (1)	138 @ 1400 rpm (187 Nm @ 1400 r/min)
SAE Net (2)	135 @ 1400 rpm (180 Nm @ 1400 r/min)

(1) Gross engine horsepower or torque at flywheel per SAE J270 specification.

(2) Net engine horsepower or torque at flywheel per SAE J270 specification

POWER CURVE



ELECTRICAL

System voltage	12 volts, negative ground
Battery	575 cold cranking amps at 0°F (−18°C)
Alternator	39 amps

POWER TRAIN

Transmission: 4 speed sliding spur gear with full power shuttle and torque converter. Permits on-the-go shifting up from 2nd to 3rd to 4th and back down from 4th to 3rd.

Torque converter: Single stage hydrokinetic type (2.78 to 1 ratio).

Reversing unit: Full power hydraulic clutches.

Brakes: Individual or simultaneous foot actuated, hydraulic self-adjusting, 6.5" (165 mm) bands and disc with over-center type parking brake.

Final drives: Multiple gear reduction.

AXLES RATINGS

FRONT	
Dynamic	36,000 lbs (16 329 kg)
Static	9,000 lbs (4082 kg)
REAR	
Dynamic	54,000 lbs (24 494 kg)
Static	13,500 lbs (6123 kg)

STEERING

Power steering	Hydrostatic
Pump capacity	6.4 gpm (24 l/min)
Turning ratio (stop to stop)	2.75
Steering cylinders (2)	1.5" dia x 6.5" stroke
Double acting	(38 mm dia x 165 mm stroke)

SERVICE CAPACITIES

	U.S.	Litres
Cooling system		
w/heater	18 qt	17
w/o heater	14 qt	13.2
Fuel tank	23.5 gal	89
Engine oil		
w/filter	7 qt	6.6
w/o filter	6 qt	5.7
Power shuttle	8 qt	7.6
Transaxle	20 qt	18.9
Hydraulic reservoir		
w/filter	10.8 gal	41.0
w/o filter	10.5 gal	39.7
Steering system total	3 qt	2.8
reservoir fill	1 qt	0.9

TRAVEL SPEEDS—MPH (km/h)

Engine at full throttle, 14.9 x 24, R4 tires.

	FIRST	SECOND	THIRD	FOURTH
Forward	3.3 (5.4)	6.4 (10.3)	12.0 (19.2)	20.9 (33.7)
Reverse	3.0 (4.8)	5.7 (9.2)	10.7 (17.3)	18.2 (29.3)

480D TIRES

	SIZE	PLY RATING	TREAD	PRESSURE PSI (kPa)
FRONT	*7.50 x 16	6	(I1) rib	36 (248)
	7.50 x 16	10	(I1) rib	60 (414)
	8.00 x 16	10	(F3) truck tread	64 (441)
	11L x 16	10	(F3) truck tread	52 (359)
REAR	14.9 x 24	6	(R4) utility traction	20 (138)
	16.9 x 24	6	(R4) utility traction	18 (124)
	17.5L x 24	6	(R4) industrial suregrip	16 (110)
	**17.5L x 24	8	(R4) industrial suregrip	22 (152)

*Used on drawbar and loader landscaper tractors only

**Must be used on machines equipped with Extendahoe

TURNING CLEARANCE CIRCLE

With brakes	20' 1" (6.12 m)
Without brakes	23' 5" (7.14 m)

480D Backhoe

HYDRAULIC SYSTEM

Hydraulic pump: Front mounted, positive displacement, gear type.

Pump capacity: 23.9 gpm @ 2100 rpm @ 2200 psi (90.5 l/min @ 2100 r/min @ 15 168 kPa).

Control valve main relief pressure: 2200 psi (15 168 kPa).

Filtration: 15 micron, full flow replaceable cartridge on return line. Condition indicator light for filter.

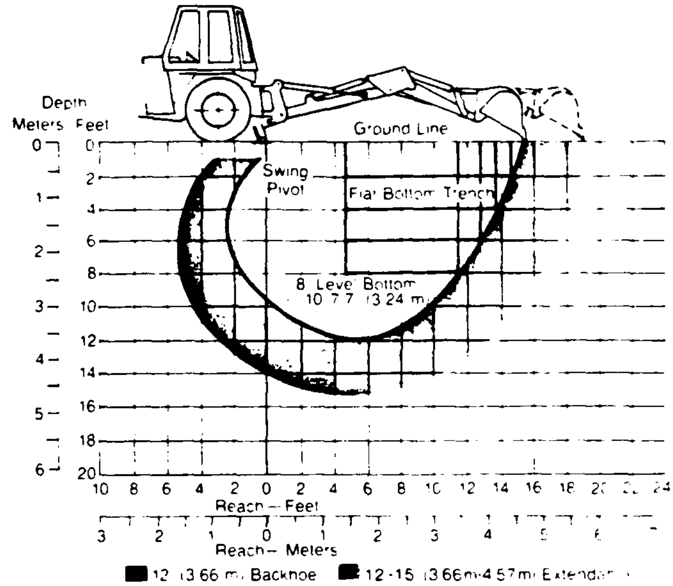
Backhoe control valve: Sectional four spool valve — boom, dipper, bucket, and swing. Foot or optional hand swing, regeneration and hydraulic cushioned swing stops. Mono-cast two spool stabilizer valve with pilot checks.

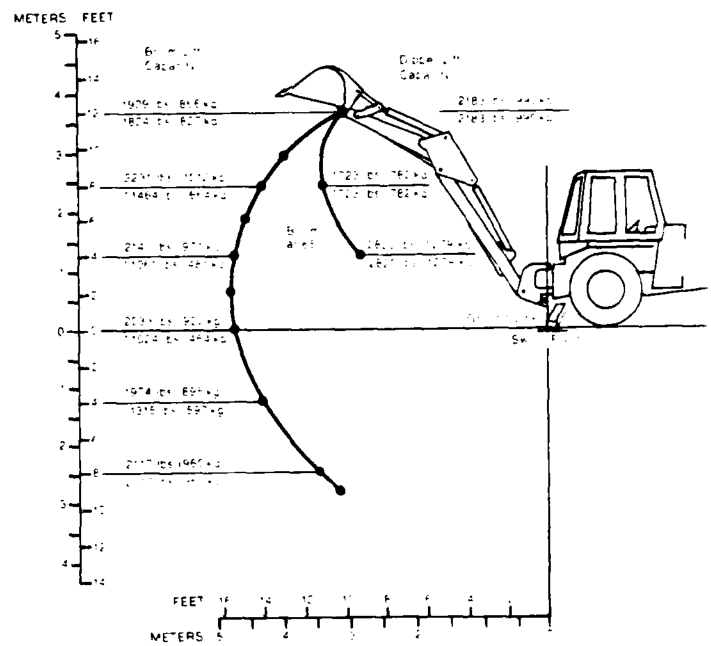
Hydraulic lines: Steel tubing with brazed or flared fittings and wire braid, high pressure hose with crimped full flow fittings.

Backhoe cylinders:

Stabilizers (2) Std	3" dia x 16.38" stroke, 1.75" rod (76 mm dia x 416 mm stroke, 44 mm rod)
(2) Opt	3.5" dia x 16.38" stroke, 1.75" rod (89 mm dia x 416 mm stroke, 44 mm rod)
Swing (2)	3.5" dia x 11" stroke, 1.5" rod (89 mm dia x 279 mm stroke, 38 mm rod)
Boom (1)	4" dia x 38.1" stroke, 1.75" rod (102 mm dia x 968 mm stroke, 44 mm rod)
Dipper (1)	3.5" dia x 33.12" stroke, 2" rod (89 mm dia x 841 mm stroke, 51 mm rod)
Bucket (1)	3.25" dia x 26.3" stroke, 2" rod (83 mm dia x 668 mm stroke, 51 mm rod)
Dipper Ext. (1)	3" dia x 36.4" stroke, 1.5" rod (76 mm dia x 925 mm stroke, 38 mm rod)

DIG DEPTH CHART





LIFT CAPACITY CHART—12′ (3.66 m) Backhoe*

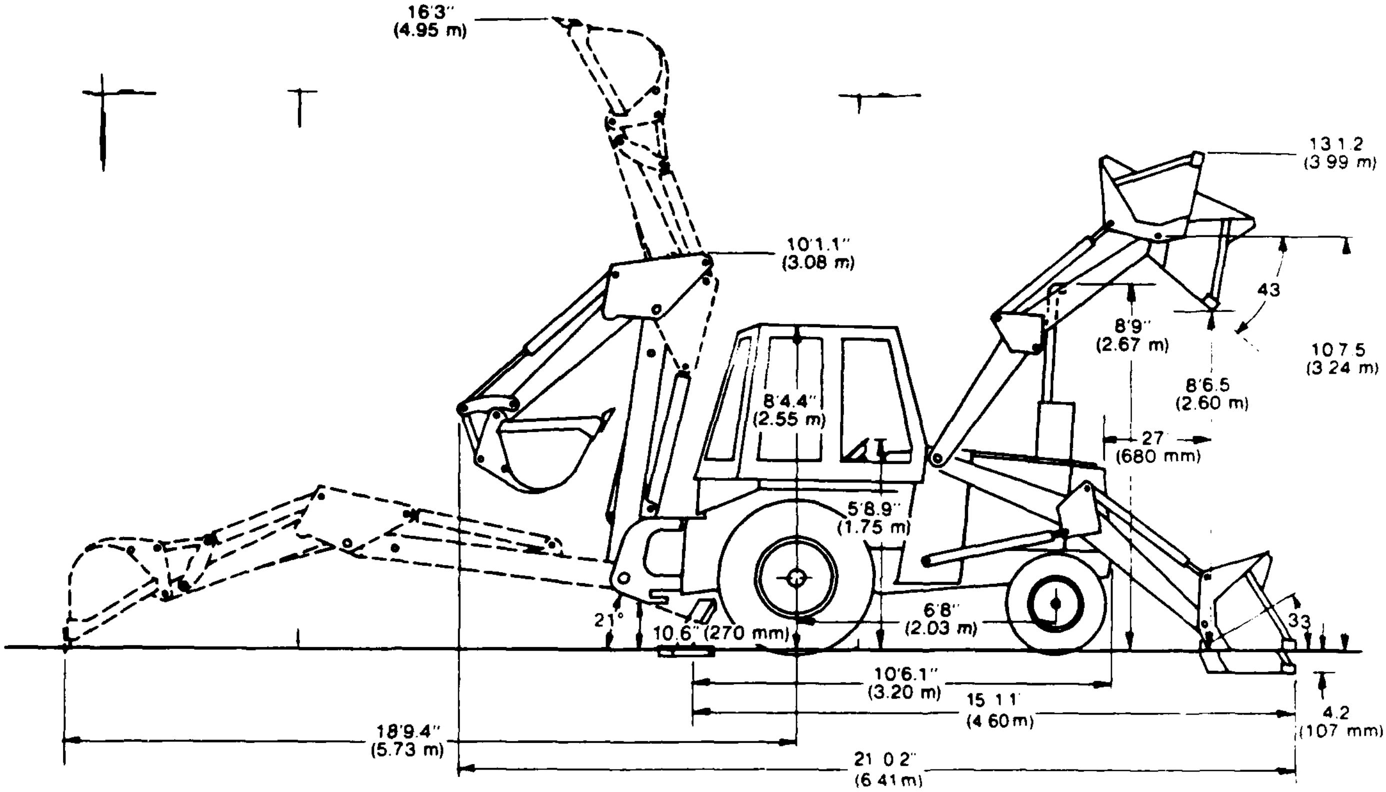
1. Lift capacity figures on this chart are 87% of the maximum lift force per SAE Definition J31 and J49 at 2200 psi (15 168 kPa) system relief pressure.
2. Top numbers lift capacity within 45° either side of prime mover.
3. Bottom numbers lift capacity anywhere within full swing arc.
4. *Figures are stability limited and 75% of tipping load.
5. Figures stated are determined by static tests and do not include dynamic factors.

*For Extendahoe lift capacities refer to operator's manual.

OPERATIONAL DATA—12′ (3.66 m) Backhoe and 12′-15′ (3.66 m-4.57 m) Extendahoe*

	12′ (3.66 m) Backhoe	12′-15′ (3.66 m-4.57 m) Extendahoe RETRACTED	EXTENDED
Digging depth—SAE	12′ 0.3" (3.67 m)	12′ 1.8" (3.70 m)	15′ 1.8" (4.62 m)
Overall reach from rear axle centerline	18′ 9.4" (5.73 m)	18′ 10.1" (5.74 m)	21′ 9" (6.63 m)
Digging radius from swing pivot	15′ 8.6" (4.79 m)	15′ 9.3" (4.81 m)	18′ 8.2" (5.70 m)
Loading height	8′ 5.1" (2.57 m)	7′ 7.4" (2.32 m)	8′ 8.7" (2.66 m)
Loading reach	7′ 3.2" (2.22 m)	8′ 3" (2.52 m)	11′ 0.5" (3.37 m)
Swing arc	180°	180°	180°
Bucket rotation—#1 position	141.7°	135.2°	135.2°
#2 position	131.2°	125.7°	125.7°
Stabilizer spread—operating position	8′ 10.4" (2.70 m)	8′ 10.4" (2.70 m)	8′ 10.4" (2.70 m)
Stabilizer spread—transport position	7′ 3" (2.21 m)	7′ 3" (2.21 m)	7′ 3" (2.21 m)
Digging force, bucket cylinder, SAE	7598 lb (33 798 N)	7748 lb (34 467 N)	7748 lb (34 467 N)
Digging force, dipper cylinder, SAE	4509 lb (20 055 N)	4606 lb (20 487 N)	3333 lb (14 825 N)
Leveling angle (maximum slope on which backhoe will make vertical cut)	10°	10°	10°

480D Loader/Backhoe Dimensional Data



TRACTOR

Overall length	10'6.1" (3.20 m)
Overall width	6'3.3" to 6'11.1" (1.91 m to 2.11 m)
Height: to top of canopy	8'4.5" (2.55 m)
Height: to top of cab	8'4.4" (2.55 m)
Height: to top of exhaust stack	8'9" (2.67 m)
Height: to top of steering wheel	5'8.9" (1.75 m)
Ground clearance (tractor main frame)	12.6" (321 mm)
Front wheel tread	4'11.1" to 5'2.2" (1.50 m to 1.58 m)
Rear wheel tread	5'0.2" to 5'6.2" (1.53 m to 1.68 m)
Wheel base	6'8" (2.03 m)

LOADER

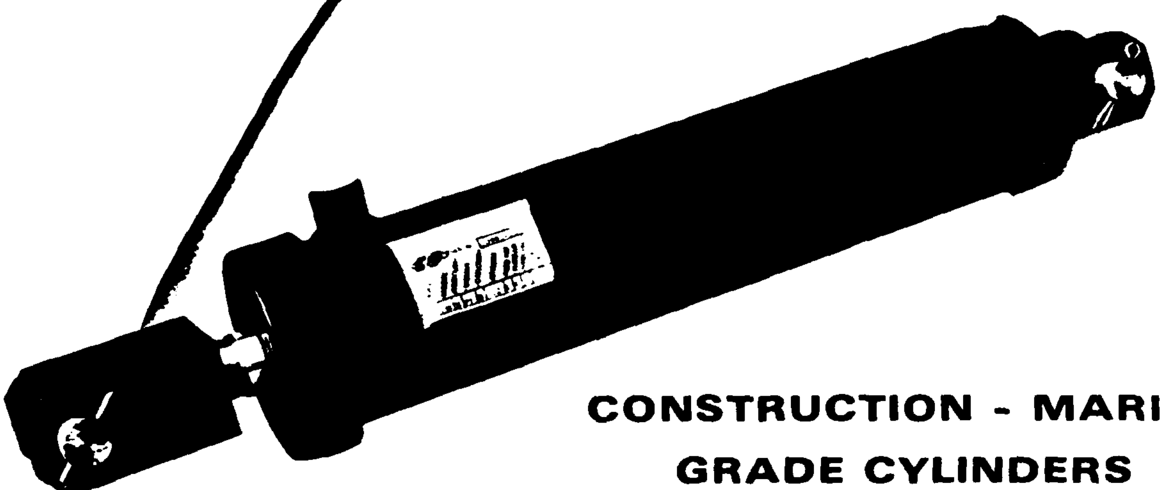
GENERAL PURPOSE BUCKET	SHORT LIP	LONG LIP
Overall length	15'1.1" (4.60 m)	15'6.8" (4.75 m)
Overall width	6'7" (2.00 m)	6'8" (2.01 m)
Overall operating height	13'1.2" (3.99 m)	13'5.8" (4.11 m)
Height to bucket hinge pin	10'7.5" (3.24 m)	10'7.5" (3.24 m)
Digging depth below ground—bucket flat	4.2" (107 mm)	4.2" (107 mm)
Dump clearance full height 43° dump	8'6.5" (2.60 m)	8'2.7" (2.51 m)
Dump angle at full height	43°	43°
Dump reach at full height 43° dump	27" (685 mm)	31.1" (791 mm)
Bucket rollback at groundline	33°	33°

BACKHOE

	12' (3.66 m)	EXTENDAHOE RETRACTED	EXTENDAHOE EXTENDED
Overall length—transport: Short lip bucket	21'0.2" (6.41 m)	21'3.8" (6.50 m)	N A
Long lip bucket	21'7.9" (6.64 m)	21'9.5" (6.64 m)	N A
Overall reach from rear axle centerline	18'9.4" (5.73 m)	18'10.1" (5.74 m)	21'9" (6.63 m)
Overall height, maximum	16'3" (4.95 m)	16'3.3" (4.96 m)	19' (5.79 m)
Transport height	10'1.1" (3.08 m)	10'5.7" (3.19 m)	N A
Overall width—transport	7'3" (2.21 m)	7'3" (2.21 m)	7'3" (2.21 m)
Ground clearance at backhoe main frame	10.6" (270 mm)	10.3" (262 mm)	10.3" (262 mm)
Angle of departure	21°	21°	21°

NOTE: Specifications taken with 11L x 16, 10PR front tires, 17.5L x 24, 6PR rear tires, ROPS canopy 12' (2.66 m) 26D backhoe with 24" (610 mm) trenching bucket, loader with 74" (1.88 m) short lip bucket and standard equipment unless otherwise specified.

Cunningham HYDRAULIC CYLINDERS



CONSTRUCTION - MARINE GRADE CYLINDERS

3,500 p.s.i. Working Pressure
5,000 p.s.i. Non-Shock

MODEL CM SPECIFICATIONS

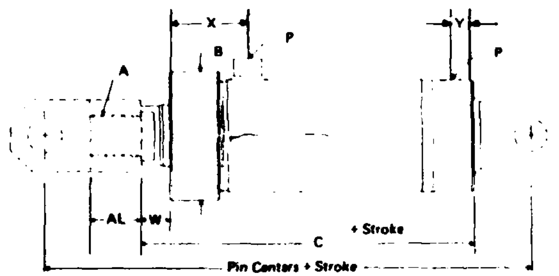
- HIGH TENSILE CHROME PLATED PISTON RODS
- PRECISION HONED STEEL TUBING
- MOLY-URETHANE ROD AND PISTON SEALS
- GLASS FILLED URETHANE ROD WIPER

OPTIONS

- STAINLESS STEEL HI TENSILE ROD
- SELF ALIGNING SPHERICAL BUSHINGS
- INTEGRAL COUNTERBALANCE VALVES
- INTEGRAL PILOT OPERATED CHECK VALVES
- S.A.E. STRAIGHT THREAD PORTS

CATALOG NO. 582CM

Cunningham Manufacturing Co.
18 SOUTH WEBSTER STREET • SEATTLE, WASHINGTON 98108 • (206) 67-3713

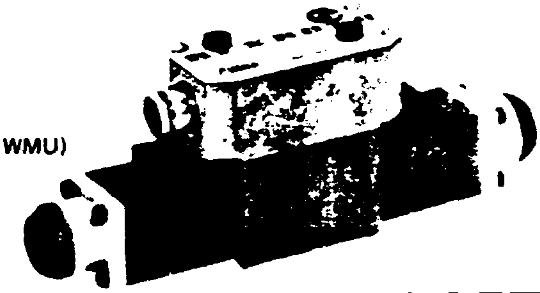


BORE	MODEL	ROD	A THREAD	AL	B	C	P NPT	OPTIONAL STRAIGHT THREAD SAE PORT	W	X	Y	PINCENTERS + STROKE: SPHERICAL BUSHING MOUNT — B1	PINCENTERS + STROKE: CLEVIS MOUNT P-1	PINCENTERS + STROKE: EYE MOUNT P-3	ROD ATTACHMENT PART NO: ROD CLEVIS	ROD ATTACHMENT PART NO: ROD EYE	BORE
1 1/2	CM	5/8	1/2 20	3/4	2 1/4	5 5/8	1/4	4 (7/16 20)	1	1 3/4	1/2	8 1/8	7 7/8	7 7/8	212	112	1 1/2
1 1/2	CM	1	3/4 16	1 1/8	2 1/4	5 5/8	1/4	4 (7/16 20)	1	1 3/4	1/2	8 1/8	8 [illegible]	8 7/16	221	121	1 1/2
2	CM	1	3/4 16	1 1/8	2 7/8	6 1/4	3/8	6 (9/16 18)	1	2 1/16	5/8	8 3/4	9 5/8	9 9/16	221	121	2
2	CM	1 3/8	1-14	1 1/8	2 7/8	6 1/4	3/8	6 (9/16 18	1	2 1/16	5/8	8 3/4	9 5/8	10 5/16	223	133	2
2 1/2	CM	1	3/4 16	1 1/8	3 1/2	6 5/8	1/2	8 (3/4 16)	1	2 1/16	5/8	8 7/8	9 3/4	9 11/16	221	121	2 1/2
2 1/2	CM	1 3/8	1-14	1 1/8	3 1/2	6 5/8	1/2	8 (3/4 16)	1	2 1/16	5/8	8 7/8	9 3/4	10 7/16	223	133	2 1/2
2 1/2	CM	1 3/4	1-14	1 5/8	3 1/2	6 5/8	1/2	8 (3/4 16)	1	2 1/16	5/8	8 7/8	10 9/16	10 7/16	231	133	2 1/2
3 1/4	CM	1 3/8	1-14	1 5/8	4 1/2	7 1/16	1/2	8 (3/4 16)	15/16	2 1/4	3/4	10 1/16	11 1/2	11 5/8	231	133	3 1/4
3 1/4	CM	1 3/4	1 1/4 12	2	4 1/2	7 1/16	1/2	8 (3/4 16)	15/16	2 1/4	3/4	10 1/16	12 5/16	12	241	141	3 1/4
3 1/4	CM	2	1 1/2 12	2	4 1/2	7 1/16	1/2	8 (3/4 16	15/16	2 1/4	3/4	10 1/16	12 5/16	12	242	142	3 1/4
4	CM	1 3/4	1 1/4 12	2	5 1/4	7 7/8	3/4	12 (1 1/16 12)	1	2 5/8	3/4	12 1/8	13 3/4	13 7/16	241	141	4
4	CM	2	1 1/2 12	2	5 1/4	7 7/8	3/4	12 (1 1/16 12)	1	2 5/8	3/4	12 1/8	13 3/4	13 7/16	242	142	4
4	CM	2 1/2	1 1/2 12	2	5 1/4	7 7/8	3/4	12 (1 1/16 12)	1	2 5/8	3/4	12 1/8	13 3/4	13 7/16	242	142	4
5	CM	2	1 1/2 12	2 1/4	6 1/2	8 1/4	3/4	12 (1 1/16 12)	1	3	3/4	13 3/4	15 [illegible]	15	251	151	5
5	CM	2 1/2	1 3/4 12	2 1/4	6 1/2	8 1/4	3/4	12 (1 1/16 12)	1	3	3/4	13 3/4	15 1/2	15	252	152	5
5	CM	3	1 7/8 12	3	6 1/2	8 1/4	3/4	12 (1 1/16 12)	1	3	3/4	13 3/4	16 1/2	16	261	161	5
5	CM	3 1/2	1 7/8 12	3	6 1/2	8 1/4	3/4	12 (1 1/16 12)	1	3	3/4	13 3/4	16 1/2	16	261	161	5
6	CM	2 1/2	1 7/8 12	3	8	10	3/4	12 (1 1/16 12)	1 1/2	3 1/4	1 1/8	16	18	17 1/2	261	161	6
6	CM	3	1 7/8 12	3	8	10	3/4	12 (1 1/16 12)	1 1/2	3 1/4	1 1/8	16	18	17 1/2	261	161	6
6	CM	4	2 1/2 12	3 1/2	8	10	3/4	12 (1 1/16 12)	1 [illegible]	3 [illegible]	1 1/8	16	19	18 5/16	272	172	6
7	CM	3	2 1/4 12	3 1/2	9	11 1/2	1	16 (1 5/16 12)	1 3/4	[illegible]	1 3/8	18 1/2	21	20 5/16	271	171	7
7	CM	4	2 1/2 12	3 1/2	9	11 1/2	1	16 (1 5/16 12)	1 3/4	3 [illegible]	1 3/8	18 1/2	21	20 5/16	272	172	7
7	CM	5	3-12	3 1/2	9	11 [illegible]	1	16 (1 5/16 12)	1 3/4	3 5/8	1 3/8	18 1/2	21 1/4	21	282	192	7
8	CM	3 1/2	2 1/2 12	3 1/2	10 1/4	12 [illegible]	1	16 (1 5/16 12)	1 3/4	4	1 3/4	21 1/8	22 5/8	22	281	181	8
8	CM	4	3 12	3 [illegible]	10 1/4	12 [illegible]	1	16 ([illegible]	1 3/4	4	1 3/4	21 1/8	22 5/8	22 5/8	282	192	8
8	CM	5 1/2	3 12	3 [illegible]	10 1/4	12 [illegible]	1	16 (1 5/16 12)	1 3/4	4	1 3/4	21 1/8	22 5/8	22 5/8	282	192	8
10	CM	5	3 1/4 12	3 [illegible]	15 [illegible]	15	1 1/4	20 (1 5/8 12)	[illegible]	[illegible]	1 1/4	25	26 3/4	26 5/8	2101	1101	10
12	CM	5 1/2	3 1/2 12	4	18 [illegible]	18	1 1/2	20 (1 5/8 12)	2	5 [illegible]	1 7/8	30	31 5/16	31 5/8	2121	1121	12

Directional Control Valve

- ANSI D01 configuration
- 3 or 4 way, direct operated design
- Flows up to 16 GPM and pressures to 4600 psi
- Operators available:
  - Single or double solenoids, AC or wet-pin DC (WE)
  - Hydraulic or pneumatic pilot (WH and WP)
  - Hand lever (WMM)
  - Roller cam (WMR and WMU)
  - Lockable hand knob (WMD)

●**Refer to:**
RA 23177 (WE)
RA 22782 (WH)
RA 22778 (WP)
RA 22277 (WMM)
RA 22275 (WMR & WMU)
RA 22279 (WMD)



Size WE6·1/4" Up to 16 GPM Up to 4600 psi — Direct Operated

Ordering Code

4 WE 6 CB5X/OF A W110R N DL B08 V/5

NO. OF SERVICE PORTS
- 3 = 3 way
- 4 = 4 way

SPOOL OPERATOR
- WE = Solenoid
- WH = Hydraulic pilot
- WP = Pneumatic pilot
- WMM = Hand lever
- WMR = Roller cam (horizontal)
- WMU = Roller cam (vertical)
- WMD = Rotary knob

SIZE 6 (1/4" ANSI D01)

SPOOL (Refer to Following Page)

SINGLE SOLENOID OPERATOR (WE)
- Omit = Std. 2 or 3 pos. valve; 2 pos. valves using spools E thru W only, spring offset-center pos. to one side
- A = Solenoid "A" only
- B = Solenoid "B" only

DESIGN SERIES

SPOOL RETURN OPERATOR
- Omit = Spring return
- F = Detents (WMM only)
- O = Without springs
- OF = Without springs, with detents

SOLENOID (WE)
- A = Wet pin

SEALS
- Omit = Buna-N
- V = Viton (standard)

THROTTLE ORIFICE
- Omit = Not required
- B08 = Throttle dia. 0.031" (0.8 mm)
- B10 = Throttle dia. 0.034" (1.0 mm)
- B12 = Throttle dia. 0.047" (1.2 mm)

ELECTRICAL CONNECTIONS (WE)
- Z4 = Small plug-in connector (standard)
- Z5 = Large plug
- Z5L = Large plug w/ind. lights
- **D = Central terminal box (standard)
- DL = Central terminal box w/ind. lights
- DZ = Central terminal box w/plug-in connector "Z"
- DZL = Central terminal box w/plug-in connector "Z" w/ind. lights

***MANUAL OVERRIDE (WE)**
- Omit = Without override
- N = Manual override (standard)

SOLENOID VOLTAGES (WE)
- Omit = 120 volt AC, 60 Hz.
- W + voltage + Hz. = All other AC solenoids
- G + voltage = DC solenoids (12 v DC)
- W110R = DC solenoid with 110 volt AC rectifier for all frequencies. ***Order with "Z5" plug only.

*Available on WE and WP only
**Rectifier N/A
***Lights N/A

Description

Rexroth Size 6 (1/4") directional control valves are direct acting miniature controls. The command signal can be electric (AC or DC), pneumatic, hydraulic or manual (roller cam, hand lever or rotary knob).

Operator forces act directly on the spool. Three position valves, in addition to controlling forward/reverse motion, have a center of neutral position. The flow pattern in the center position is determined by the spool selected. Center position (WE version) is achieved when the solenoids are de-energized. Springs center the spool in the valve body.

Pushbutton manual override(s) are available on WE and WP versions to allow manual spool shifting in the absence of electrical or air supply.

Solenoids used for the WE6 Design Series 50 valves are of the "wet-pin" design. The wet-pin solenoid is available in designs for operation with AC or DC electrical systems. The solenoid internal parts are pressure sealed to the tank port within the valve body and are therefore insensitive to moisture and dirt contamination.

Quiet operation, (armature movement cushioned by the surrounding hydraulic oil), and excellent heat dissipation are primary advantages.

The Rexroth solenoids operate to 300°F (150°C) and exceed NEMA Class B insulation requirements.

AC Solenoid Features
- Convenient electrical connections by plug-in or central conduit box.
- Fast response - 30 ms.
- No special electrical contact protection required.

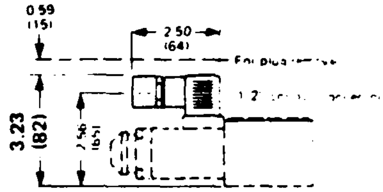
DC Solenoid Features
- Burnout resistant if mechanical sticking of the spool occurs.
- Can be operated on AC current by a built-in rectifier incorporated in the "Z5" plug-in connector.
- Insensitive to fluctuations in voltages.
- High cycle frequency (15,000 cycles per hour).
- Extremely quiet operation.

●(RA) Engineering Data Sheets provide complete technical information

Electrical Connection Options **Dimensions Inches (mm)**

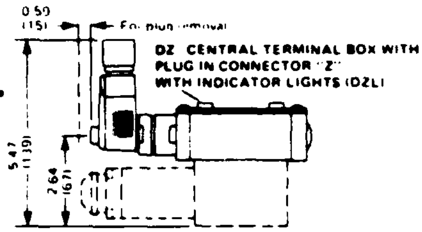
Z4

PLUG IN CONNECTOR



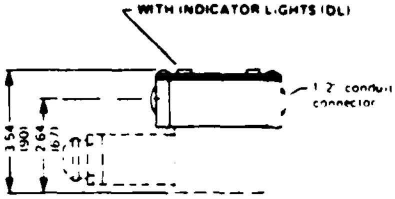
DZ DZL

DZ CENTRAL TERMINAL BOX WITH PLUG IN CONNECTOR "Z" WITH INDICATOR LIGHTS (DZL)



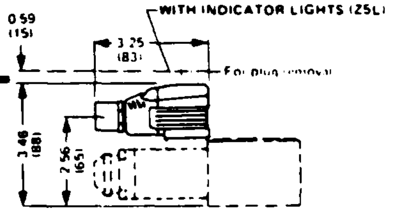
D DL

D CENTRAL TERMINAL BOX WITH INDICATOR LIGHTS (DL)



Z5 Z5L

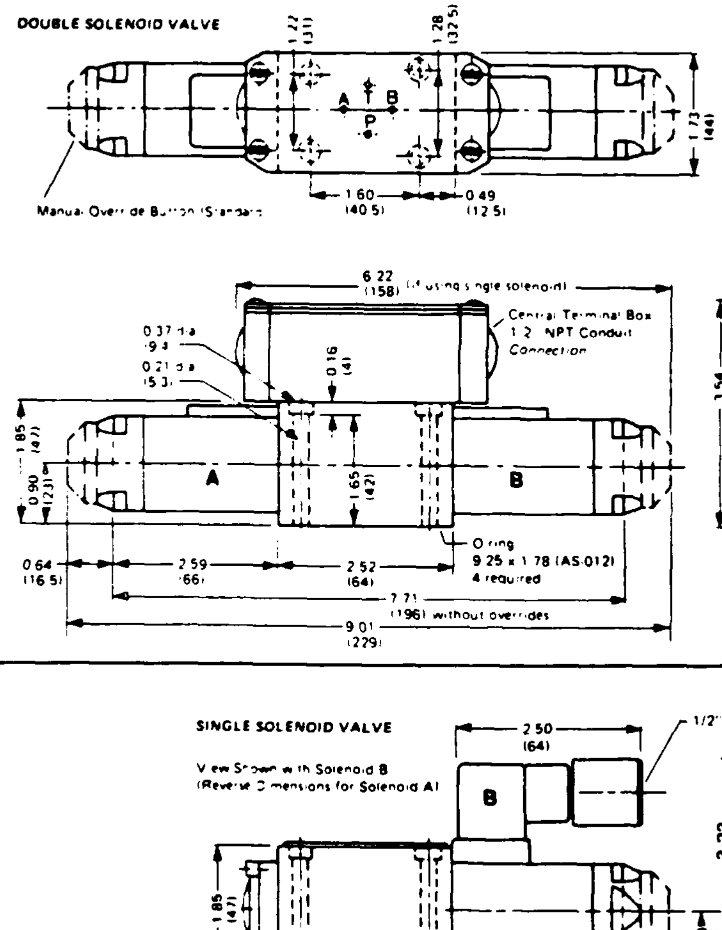
Z5 LARGE PLUG-IN CONNECTOR WITH INDICATOR LIGHTS (Z5L)



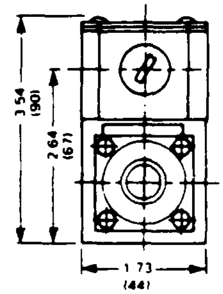
Unit Dimensions **Dimensions Inches (mm)**

WE6

DOUBLE SOLENOID VALVE

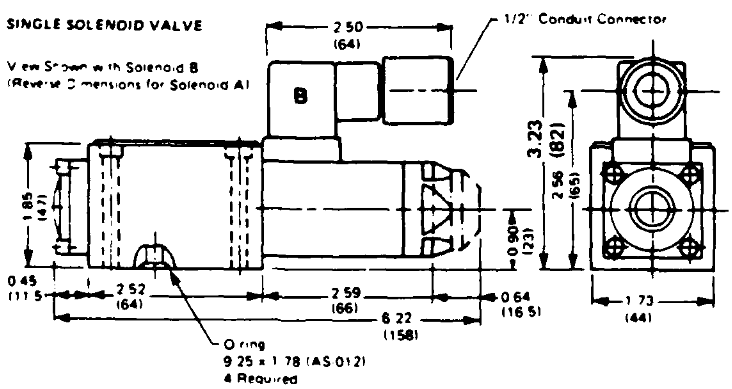


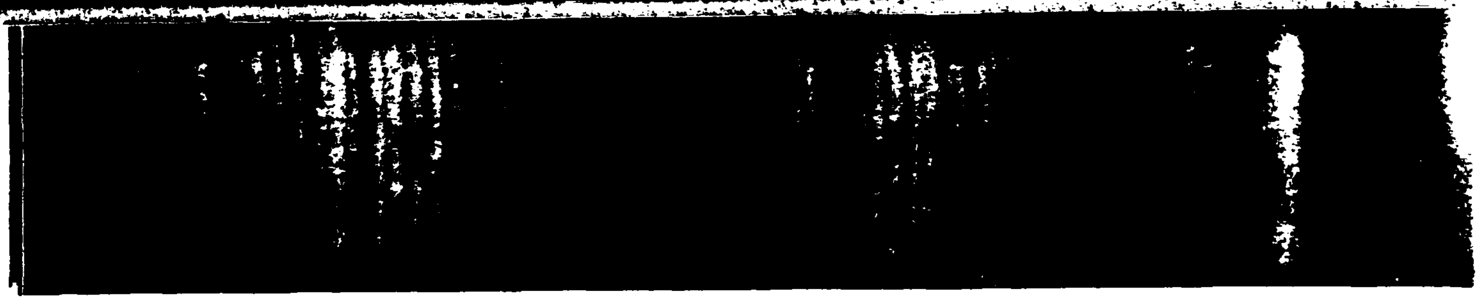
Ordering Codes
D Plain Cover
DL Cover with Lights



SINGLE SOLENOID VALVE

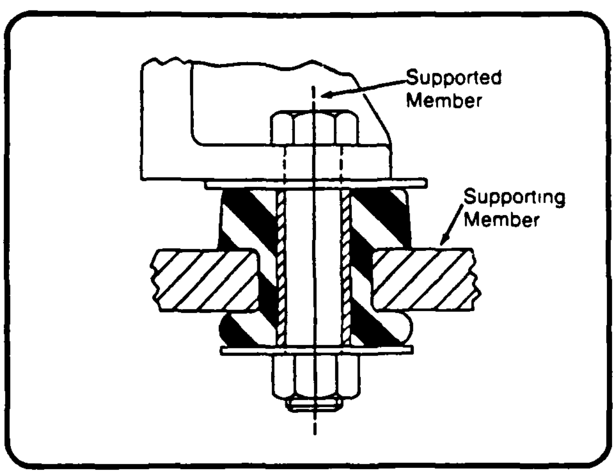
View Shown with Solenoid B
(Reverse Dimensions for Solenoid A)





Center Bonded Mounts

(CBA Series)



NOTE: Supersedes CB-1100 Series

CBA Series Center Bonded Mounts are heavy duty mounts which isolate vibration, absorb shock and attenuate noise due to structure-borne vibrations. CBA Mounts are available in ten sizes with load ratings ranging from 100 to 1,600 pounds. Natural frequency of 12 to 14 Hz.

Engineered one piece design, in which a cushion of elastomer is bonded permanently to a tubular steel inner member. This construction assures proper installation of the mount and improved fatigue life over unbonded designs. Precompression of the flexing element takes place when the bolt is tightened against the mounts inner member. CBA Series Center Bonded Mounts are available for Grade 2 or Grade 8 bolt torque capacity.

Features and Benefits

- Dynamically effective in all directions
- Misalignment capability.
- Tapered for ease of installation.
- Built-in rebound protection.
- Consistent performance.
- Space saving size.
- Long service life.
- Low cost installation.

Specification: Table 1

(All parts available from stock.)

Part Number	See Fig.	Color Code	Static Load① Rating at Deflection (Max.) lbs at in N at mm	PART DIMENSIONS A Dia. ±.015 in mm	B Dia. in mm	C Dia. ±.015 in mm	D ±.02 in mm	E ±.015 in mm	F ±.02 in mm	INSTALLATION DIMENSIONS G REF. in mm	H Dia in mm	S_D Dia. ±.03 in mm	S_R ±.015 in mm	S_T ±.03 in mm
CBA12-100	2		100 at .09 445 at 2.29	1.25 31 8	.410 .397 10.2	.950 24.1	1.44 36 6	1.07 27 2	.550 14 0	.510 13.0	—	.895 22.7	060 1 52	380 9 70
CBA12-200	2	Orange	200 at .09 890 at 2 29	1.25 31 8	.410 .397 10 2	.950 24 1	1.44 36 6	1.07 27 2	.550 14 0	510 13 0	—	.895 22 7	060 1 52	380 [illegible]
CBA20-300	2		300 at .09 1779 at 2.29	2.00 50 8	.540 .525 13.5	1.38 35.1	2.00 50.8	1.45 36.8	.750 19 1	.690 17.5	—	1.25 31 8	060 1 52	.500 12 7
CBA20-300-1	3				.545 .515 13.5						1 38 35 1			
CBA20-400	2	Orange	400 at .10 1779 at 2 54	2.00 50 8	.540 .525 13 5	1.38 35 1	2.00 50 8	1 45 36 8	750 19 1	690 17 5	—	1 25 31 8	060 1 52	500 12 7
CBA20-400-1	3	Yellow			.545 .515 13 5						1.38 35 1			
CBA24-500	2		500 at .09 2224 at 2 29	2.35 59.7	.657 .639 16.5	1.50 38.1	2.11 53.6	1.50 38.1	.690 17.5	.620 15.7	—	1.38 35 1	060 1 52	.620 15 7
CBA24-500-1	3				.655 .625 16.3						1 62 41 1			
CBA24-650	2	Orange	650 at .10 2891 at 2.54	2.35 59 7	.657 .639 16 5	1.50 38 1	2.11 53 6	1.50 38 1	.690 17 5	.620 15 7	—	1.38 35 1	.060 1 52	.620 15 7
CBA24-650-1	3	Yellow			.655 .625 16.3						1 62 41 1			
CBA28-800	2		800 at .10 3559 at 2.54	2.80 71.1	.810 .795 20.3	1.62 41.1	2.38 60 5	1.63 41 4	.690 17 5	.630 16.0	—	1.50 38 1	.060 1 52	.750 19 1
CBA28-800-1	3				.785 .755 19 6						1.62 41.1			
CBA28-1050	2	Orange	1050 at .10 4671 at 2 54	2.80 71 1	.810 795 20 3	1.62 41 1	2.38 60 5	1 63 41 4	.690 17 5	630 16 0	—	1 50 38 1	060 1 52	750 19 1
CBA28-1050-1	3	Yellow			.785 .755 19 6						1 62 41 1			
CBA33-1200	2		1200 at .11 5338 at 2.79	3.30 83 8	.810 .795 20.3	1.62 41 1	2.50 63.5	1.94 49 3	880 22 4	.810 20 6	—	1 50 38.1	060 1 52	880 22 4
CBA33-1200-1	3				.785 .755 19.6						1.62 41 1			
CBA33-1600	2	Orange	1600 at .12 7117 at 3 05	3.30 83 8	.810 .795 20 3	1.62 41 1	2 50 63 5	1 94 49 3	880 22 4	.810 20 6	—	1 50 38 1	060 1 52	880 22 4
CBA33-1600-1	3	Yellow			.785 .755 19 6						1 62 41 1			

Notes: Mounts and washers only supplied by Lord
Red figures are metric reference
Washers must be ordered separately

① These ratings are for On-Highway applications For Off-Highway use 80 percent of loads shown

Standard Series (Uninstalled)

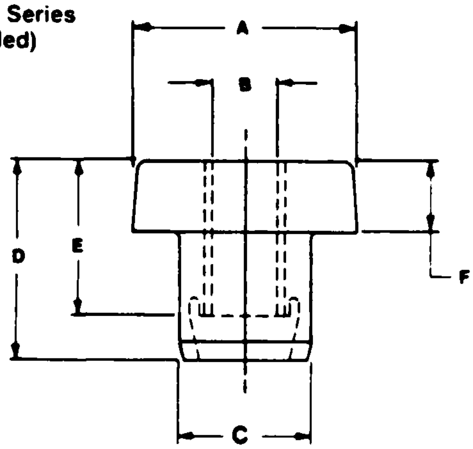


Fig. 2

High Bolt Torque Series (-1 Parts) (Uninstalled)

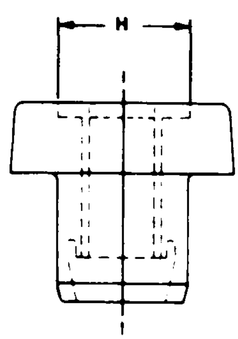


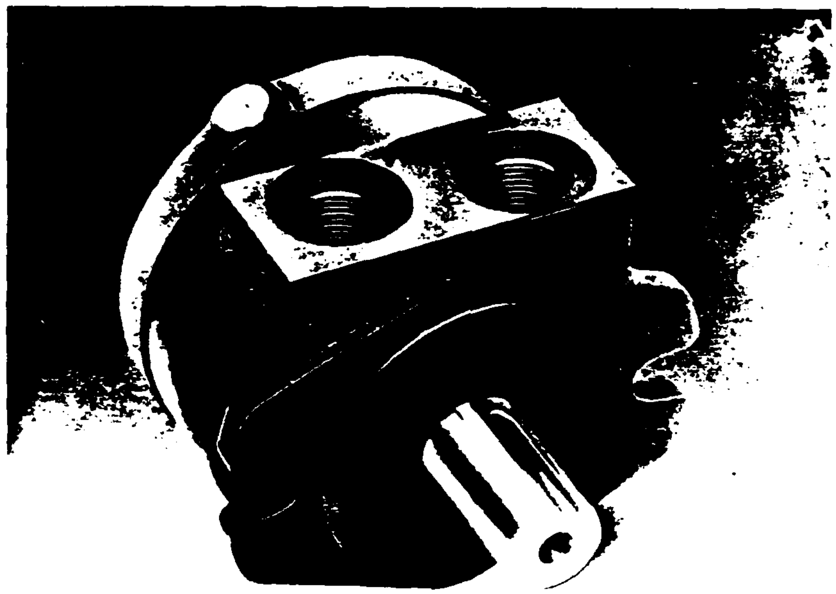
Fig. 3

For other dimensions, see Figure 2

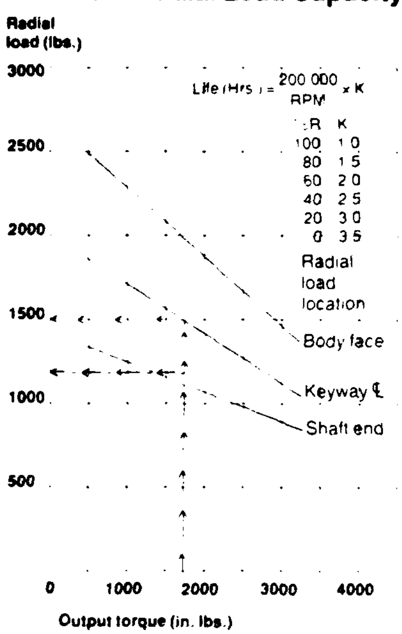
110 Series

Nichols 110 Series HTLS hydraulic motor is an extremely compact, yet powerful torque package.

This powerful hydraulic motor delivers up to 4580 in. lbs. in 5" of length, yet is very lightweight, ranging from 11¾ to 16¾ lbs. The single piece fixed axis shafting allows for high output torque. The unique IGR power element in the 110 Series is self-sealing and wear compensating, producing high volumetric efficiencies at all operating pressures throughout the life of the motor. Because the motor typically operates at less than 10 PSIG, this results in high mechanical efficiency. The 110 is built with a DU bearing system to save both space and money, making this motor ideal for moderate radial load operations. The Nichols 110 Series is available in SAE A and 4-bolt mounts and common 1" shafts, with a thru-shaft option.



Maximum Radial Load Capacity



Example

Load centered over key.
Torque = 1700 in. lbs.
Actual radial load = 1200 lbs. @ 100 RPM.
From figure = Max. radial load = 1500 lbs.

$$\text{Therefore, } \%R = \frac{1200}{1500} = 80\%$$

From Table—K = 1.5

$$\text{Calculation—Life} = \frac{200{,}000}{100} \times 1.5 = 3000 \text{ hrs}$$

Note

When using a thru-shaft, consult factory if radial load on either end is over 400 lbs. max.

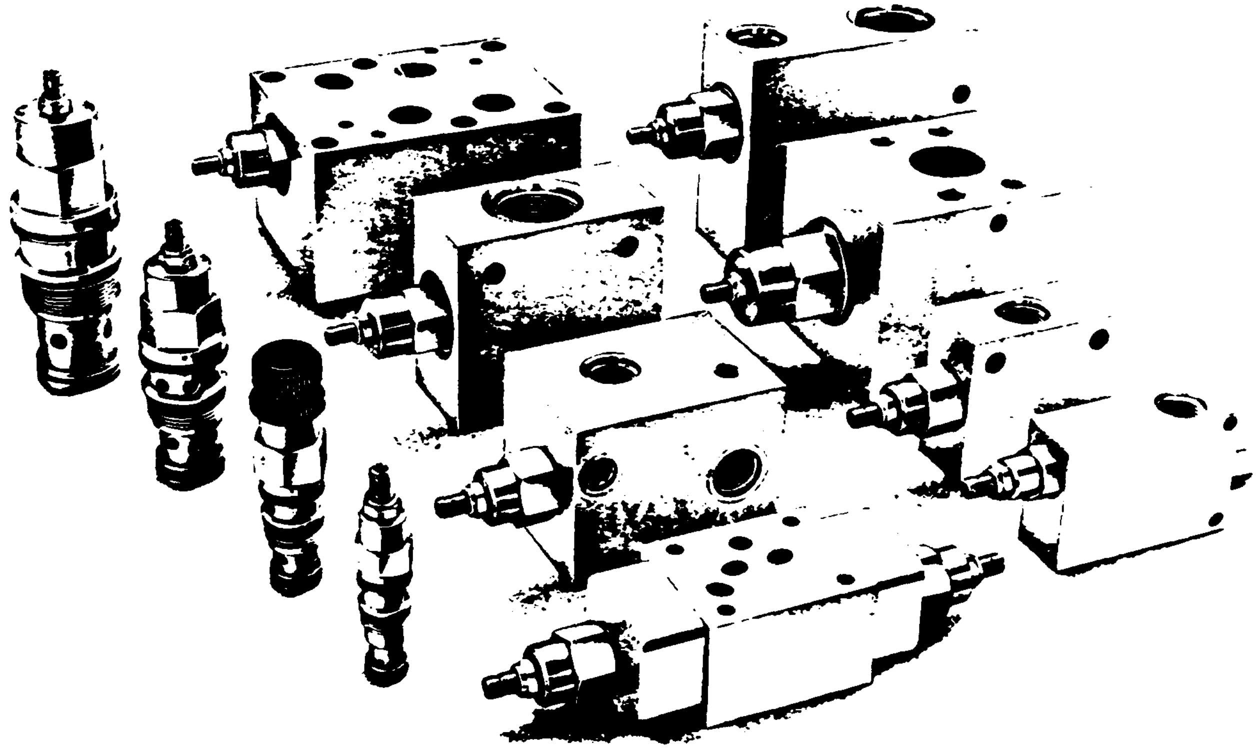
Specifications

Specifications	-1	-2	-3	-4	-5	-6	-7
Displacement (in³/rev.)	3.6	5.4	7.1	8.8	10.6	12.9	16.4
Length "L" Inches	3.67	3.86	4.05	4.24	4.43	4.68	5.0[illegible]
Weight Lbs.	11.7	12.5	13.0	13.7	14.5	15.5	16.7
Max. speed (RPM) @ 15 GPM	945	643	487	390	326	272	211
Speed (RPM) per GPM	63	43	32	26	22	18	14
Pressure (psi)							
Max. continuous	1750	1750	1750	1750	1750	1750	1500
Max. intermittent	2250	2250	2250	2250	2250	2250	2000
Max. torque (in. lbs.)							
@ max. continuous psi	881	1307	1721	2145	2584	3142	3403
@ max. intermittent psi	1141	1690	2224	2774	3339	4062	4580
*Peak back pressure (psi)	1500	1500	1500	1500	1500	1500	1500

*For continuous back pressure over 300 psi, use the external case drain. Install case drain line such that motor case will remain filled with fluid at all times.

Notes:

1. Intermittent operation is assumed to be less than (1) minute in (10).
2. (25) micron filtration, β ratio of 2, is recommended.
3. Maximum permitted oil inlet temperature—180°F.
4. Oil viscosity—minimum 50 SUS.
5. Maximum transient pressure not to exceed 4000 psig.
6. Maximum shaft thrust load capacity is 1000 lbs. outward, 500 lbs. inward.
7. If operating without radial load, operating pressures may be increased. See performance data.
8. 1" key shaft not recommended for torques over 3000 in lbs.



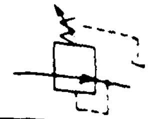
SUN Pressure Reducing and Reducing/Relieving valves maintain a constant (lower) secondary pressure in a hydraulic sub-system, regardless of variations in pressure in the primary system, eliminating the need for an additional, low pressure pump. They provide accurate pressure control for feed, clamp and hold-down circuits. Normally open, the valves regulate pump flow to the reduced pressure system to maintain the pressure at the desired level.

In addition, the Reducing/Relieving valve configuration provides an ample flow path from the reduced pressure port to tank. If flow in the secondary system reverses (e.g., a cylinder being pushed back mechanically) the valve opens and regulates secondary system flow to tank like a relief valve, to maintain the desired reduced pressure. A separate, full-capacity return line must be provided to handle pilot drain and relief flow.

With a single adjustment, SUN Reducing/Relieving valves accurately regulate secondary system pressure. The valve will modulate continuously between reducing and relieving with no hunt or surge in the transition.

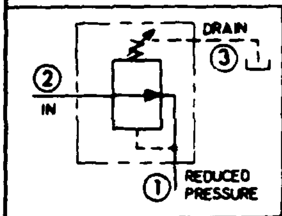
Several cartridge sizes are available with a remote air piloted pressure control feature replacing the standard pressure adjusting screw. See Circuit Savers–Section 8.

SUN Pressure Reducing and Reducing/Relieving valves are offered in a broad selection of body configurations including line mounted valves with or without reverse free-flow checks and in SUN sandwich valve configurations for all sizes of NFPA solenoid control valves, NFPA DO1 through DO6.

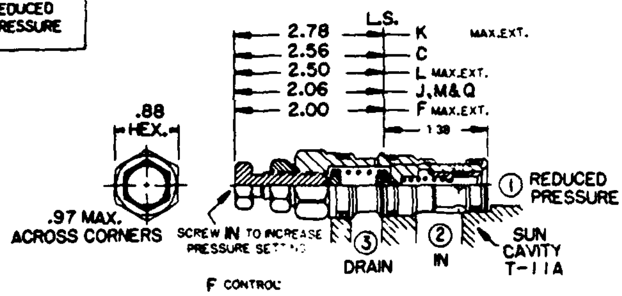


CARTRIDGES

Pilot-operated, balanced spool valves
3000 psi maximum inlet pressure
(2000 psi - adjustment ranges 'D' and 'E')



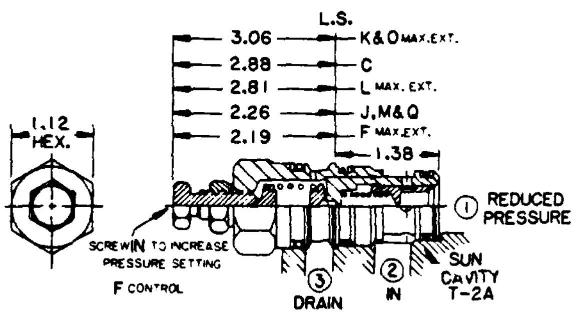
0 to 10 GPM
PILOT FLOW - 7 to 10 CU. IN./MIN.
SUN CAVITY T-11A



MODEL **PBDB** ＊＊＊
① CONTROLS
② ADJUSTMENT RANGES
③ SEALS

BASIC CARTRIDGE PRICE
28.40

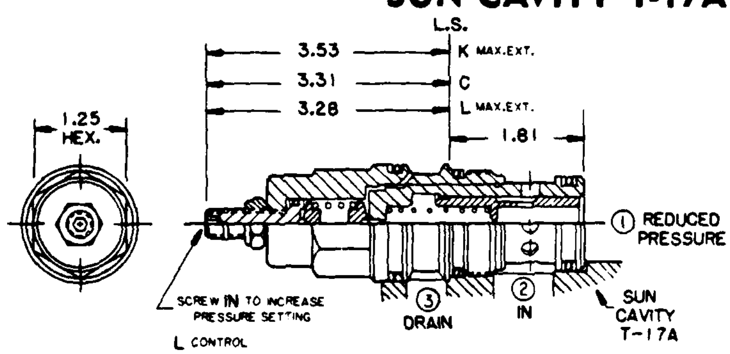
0 to 20 GPM
PILOT FLOW - 10 to 15 CU. IN./MIN.
SUN CAVITY T-2A



MODEL **PBFB** ＊＊＊
① CONTROLS
② ADJUSTMENT RANGES
③ SEALS

BASIC CARTRIDGE PRICE
[illegible]

0 to 40 GPM
PILOT FLOW 15 to 30 CU. IN./MIN.
SUN CAVITY T-17A



MODEL **PBHB** ＊＊＊
① CONTROLS
② ADJUSTMENT RANGES
③ SEALS

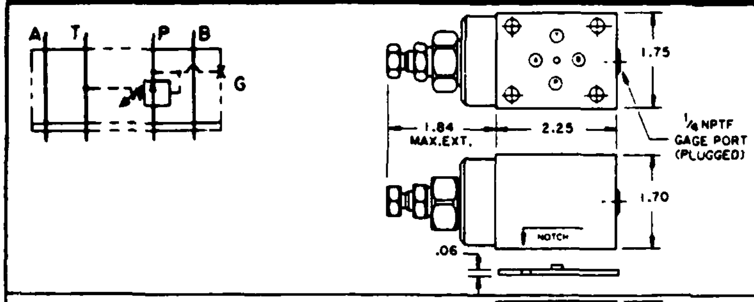
BASIC CARTRIDGE PRICE
79.[illegible]

L K O C F J M Q

NFPA D01–SANDWICH VALVES

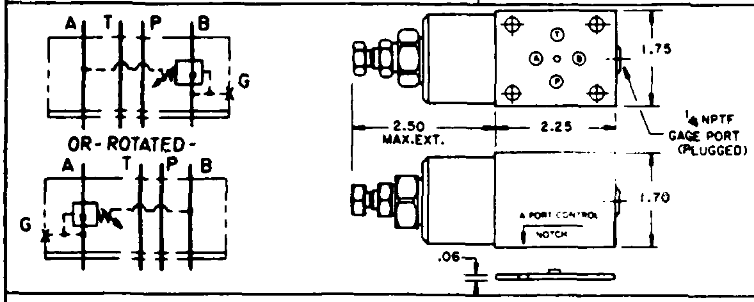
FOR USE WITH **NFPA D01** AND **CETOP 3** STANDARD SOLENOID VALVES

REDUCING VALVE SANDWICHES



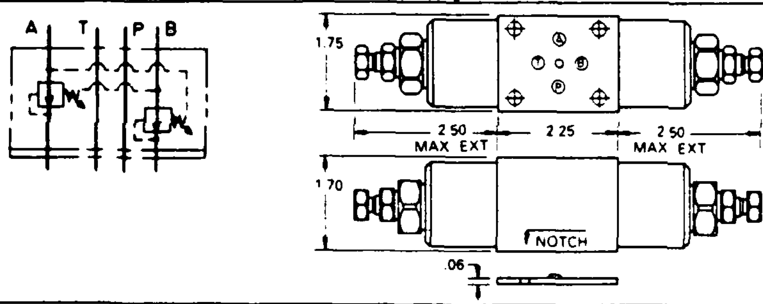
REDUCED PRESSURE ON P

MODEL **PBDB *** EBP** — BASIC MODEL PRICE 71.90



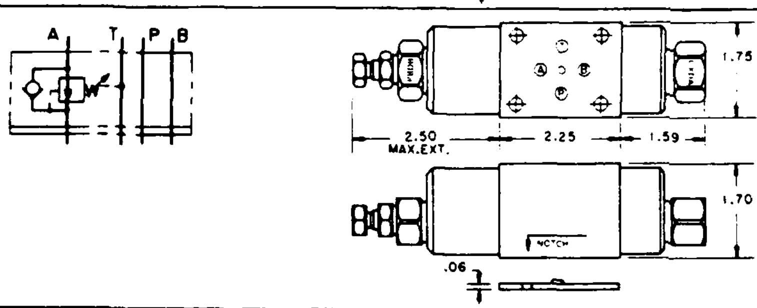
REDUCED PRESSURE ON A OR B

MODEL **PBDB *** EBA** — BASIC MODEL PRICE 67.70



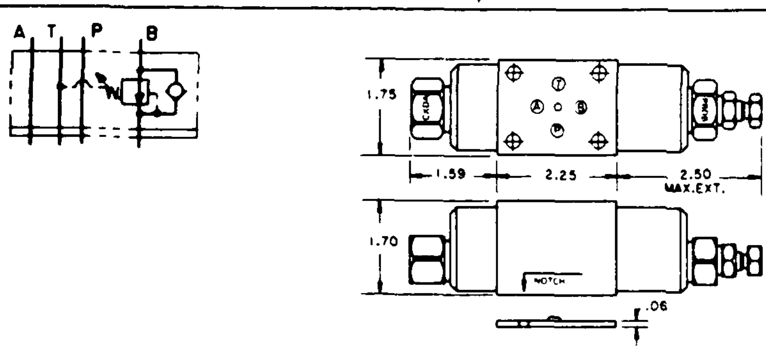
DUAL–REDUCED PRESSURE ON A AND B

MODEL **PBDB *** EBY** — BASIC MODEL PRICE 122.60



REDUCED PRESSURE ON A
WITH REVERSE FREE FLOW

MODEL **YPCA *** AA** — BASIC MODEL PRICE 107.70



REDUCED PRESSURE ON B
WITH REVERSE FREE FLOW

MODEL **YPCB *** AA** — BASIC MODEL PRICE 107.70

(a) See cartridge model PBDB *** (p. 3 02) and CXDA XA * (p. 7 02) for performance data, options and option prices

Aeroquip / Hydraulic hose

Polyon/Thermoplastic

FC374 SAE100R8

Construction: Hytrel† polyester tube, single braid high strength Kevlar† reinforcement and a black perforated polyurethane cover.

Application: Hydraulics, pneumatics and lubricating oil. For more specific information on fluid applications, see pages 19–23.

Operating Temperature Range: −65°F to +200°F (−54°C to +93°C) Except with water and water based hydraulic fluids to +150°F (+66°C) **

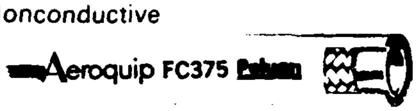
Fittings: Swaged/crimped, see Aeroquip Bulletin 5868

For complete Agency Listings: See page 32

Part Number	FC374											
Dash Size	−03	−04	−06	−08	−12	−16						
Hose I.D. (inches)	.19	.25	.38	.50	.75	1.00						
Maximum Hose O.D. (inches)	.40	.51	.66	.81	1.08	1.32						
Maximum Operating Pressure (psi)	5000	5000	4000	3500	2250	2000						
Minimum Burst Pressure (psi)	20000	20000	16000	14000	9000	8000						
Minimum Bend Radius* (inches)	1.50	2.00	2.50	4.00	8.00	10.00						
Vacuum Service (in./Hg)												
Weight per ft. (lbs.)	.04	.08	.11	.15	[illegible]	.26						

Polyon/Thermoplastic

Nonconductive



FC375 SAE100R8

Construction: Hytrel† polyester tube, single braid high strength Kevlar† reinforcement and an orange nonperforated polyurethane cover.

Application: Hydraulics and lubricating oil where nonconductivity is required. For more specific information on fluid applications, see pages 19–23. For nonconductivity information, see item 8 page 18.

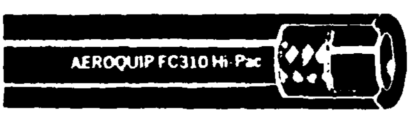
Operating Temperature Range: −65°F to +200°F (−54°C to +93°C) Except with water and water based hydraulic fluids to +150°F (+66°C) **

Fittings: Swaged/crimped, see Aeroquip Bulletin 5868

For complete Agency Listings: See page 32

Part Number	FC375											
Dash Size	−03	−04	−06	−08	−12							
Hose I.D. (inches)	.19	.25	.38	.50	.75							
Maximum Hose O.D. (inches)	.40	.51	.66	.81	1.08							
Maximum Operating Pressure (psi)	5000	5000	4000	3500	2250							
Minimum Burst Pressure (psi)	20000	20000	16000	14000	9000							
Minimum Bend Radius* (inches)	1.50	2.00	2.50	4.00	8.00							
Vacuum Service (in./Hg)												
Weight per ft. (lbs.)	.04	.08	.11	.15	.20							

HI-PAC wire braid



FC310
SAE100R2 performance

Construction: Synthetic rubber tube, patented Hi-Pac braided wire reinforcement, synthetic rubber cover

Application: Hydraulic system service with petroleum and water-glycol base fluids, for general industrial service. For more specific information on fluid applications, see pages 19–23.

Operating Temperature Range: −40°F to +200°F (−40°C to +93°C) **

Fittings: Reusable, pages 68–70
Crimped, see Aeroquip Catalog 253A

Assembly Instructions: Page 116

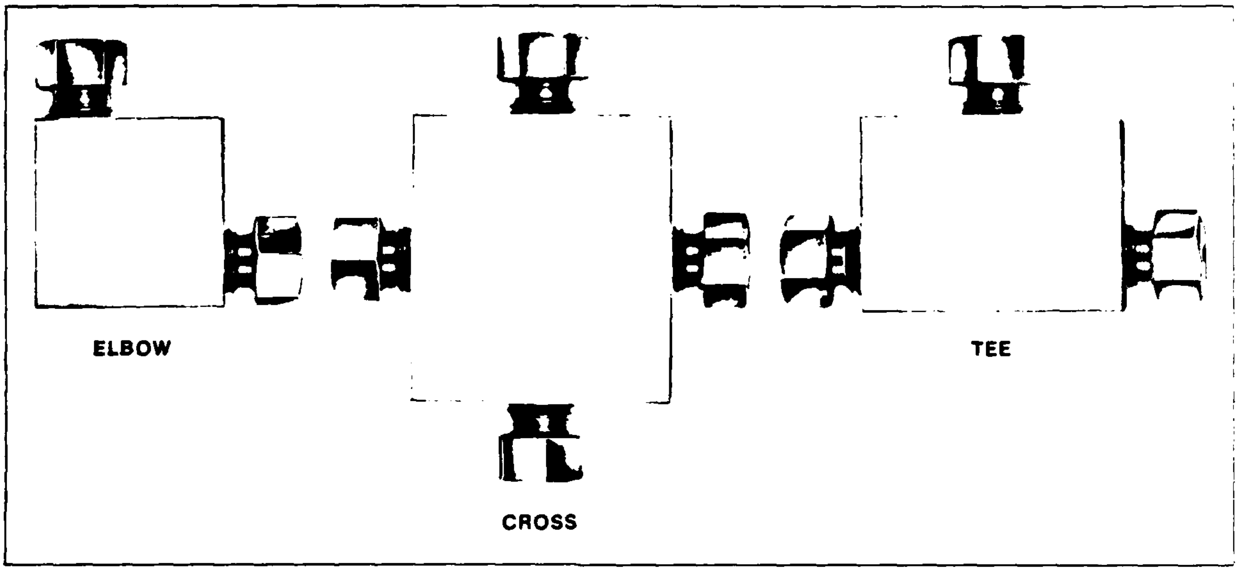
For complete Agency Listings: See page 32.

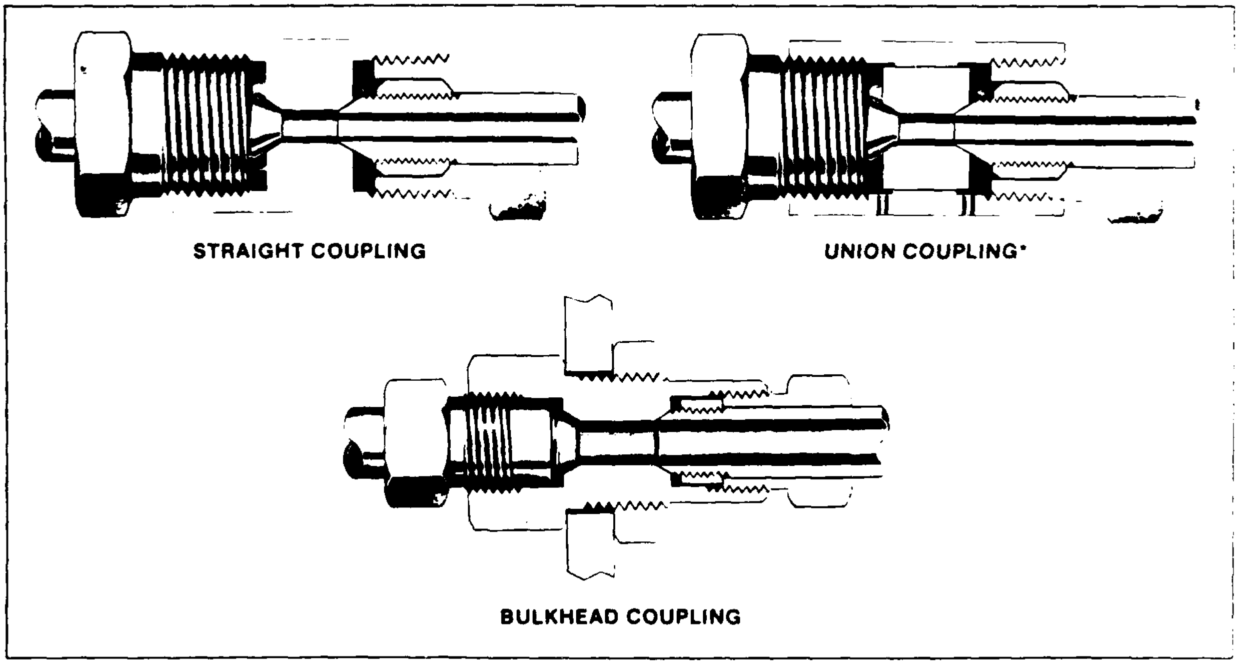
Part Number	FC310											
Dash Size	−04	−06	−08	−10	−12	−16	−20					
Hose I.D. (inches)	.26	.38	.50	.62	.75	1.00	1.25					
Maximum Hose O.D. (inches)	.55	.68	.79	.93	1.08	1.36	1.69					
Maximum Operating Pressure (psi)	5000	4000	3500	2750	2250	2000	1625					
Minimum Burst Pressure (psi)	20000	16000	14000	11000	9000	8000	6500					
Minimum Bend Radius* (inches)	3.00	3.50	5.00	6.00	7.00	9.00	11.00					
Vacuum Service (in./Hg)												
Weight per ft. (lbs.)	.21	.28	.34	.47	.53	.70	.98					

*See page 27 for bend radius data **Specific high temperature ratings are shown with each general fluid type listed on pages 19–23
†Hytrel and Kevlar are DuPont trademarks

K4

AE Fittings and Accessories





*Union coupling design offers movable insert with coned seats permitting rigid lines to be connected and disconnected readily without dismantling system

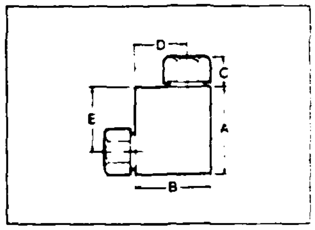
K16

AE HighPressure Fittings Series F

For 9/16" (14.3 mm) O.D. Tubing: 60,000 psi (414 MPa)*

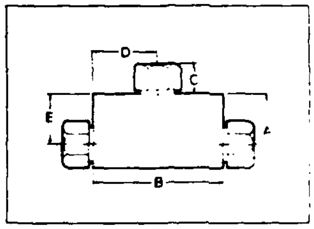
Correlated for use with series 30VM and series 60VM valves and AE HighPressure tubing

Elbow



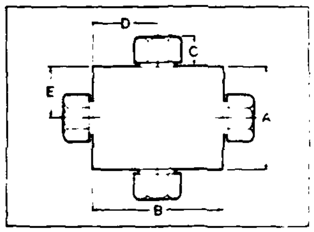
CONNEC-TION TYPE	CATALOG NUMBER	DIMENSIONS: INCHES (mm)					BLK. THK.	MINIMUM OPENING
		A	B	C	D	E		
F 562 C	CL 9900	1.88	2.62	0.81	1.88	1.12	1.50	0.188
		(47.8)	(66.5)	(20.6)	(47.8)	(28.4)	(38.1)	(4.78)

Tee



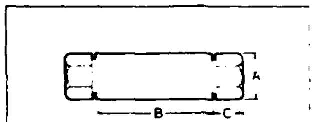
CONNEC-TION TYPE	CATALOG NUMBER	DIMENSIONS: INCHES (mm)					BLK. THK.	MINIMUM OPENING
		A	B	C	D	E		
F 562 C	CT 9990	2.12	2.62	0.81	1.31	1.38	1.50	0.188
		(53.8)	(66.5)	(20.6)	(33.3)	(35.1)	(38.1)	(4.78)

Cross



CONNEC-TION TYPE	CATALOG NUMBER	DIMENSIONS: INCHES (mm)					BLK. THK.	MINIMUM OPENING
		A	B	C	D	E		
F 562 C	CX 9999	2.75	2.62	0.81	1.31	1.38	1.50	0.188
		(69.9)	(66.5)	(20.6)	(33.3)	(35.1)	(38.1)	(4.78)

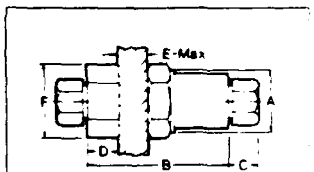
Straight Coupling & Union Coupling



See page K4 for comparison of straight vs. union coupling

CONNEC-TION TYPE	CATALOG NUMBER		DIMENSIONS: INCHES (mm)			MINIMUM OPENING
	STRAIGHT COUPLING	UNION COUPLING	A	B	C	
F 562 C	60F 9933	60UF 9933	1.38	2.19	0.81	0.188
			(35.1)	(55.6)	(20.6)	(4.78)

Bulkhead Coupling



(A = Panel hole drill size)

CONNEC-TION TYPE	CATALOG NUMBER	DIMENSIONS: INCHES (mm)						MINIMUM OPENING
		A	B	C	D	E	F	
F 562 C	60BF 9933	1.69	2.75	0.81	1.00	0.38	1.88	0.188
		(42.9)	(69.9)	(20.6)	(25.4)	(9.65)	(47.8)	(4.78)

Connection Components

All AE valves and fittings are supplied complete with appropriate glands, collars, etc. To order these components separately, use order numbers listed.

Gland AGL 90 | **Collar** ACL 90 | **Plug** AP 90

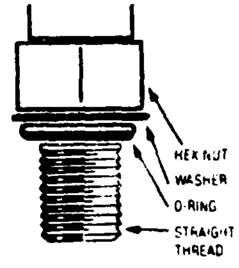
NOTE: All dimensions for reference only and subject to change

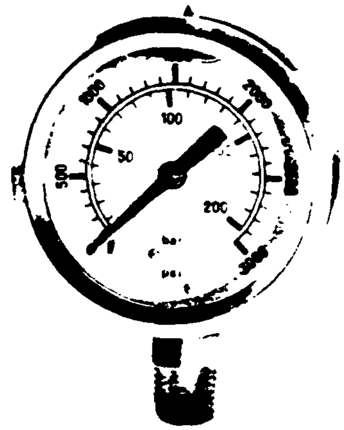
AUTOCLAVE ENGINEERS, INC. / Erie, Pennsylvania 16512, USA

All general terms and conditions of sale, including limitations of our liability, apply to all products and services sold.

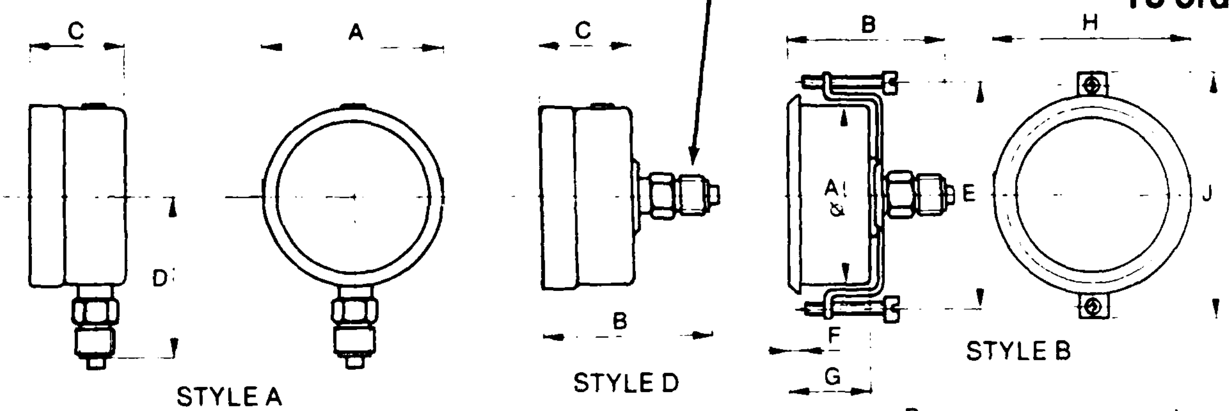
CAN FLO CORPORATION GLYCERINE FILLED 2 AND 2½ INCH

- **Stainless Steel Case and Bezel**
- **Spiral Bourdon Tube Over 600 PSI**
- **Built in Relief Valve**
- **Pressure range to 15,000 PSI**
- **Dual Scale**
- **Accuracy ± 1.6% Full Scale Deflection Center 40% of Scale otherwise 2% FSD**



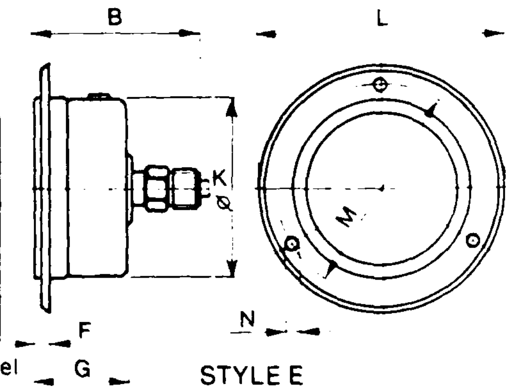


Now with SAE Straight Thread Connection To order



Size		A	B	C	D	E	F	G	H	J	K	L	M	N	
2 in.		2.09	2.24	1.22	1.97	2.33	.28	1.18	2.24	2.68	2.13	2.76	2.44	.14	in.
		53	57	31	50	59	7	30	57	68	54	70	62	3.5	mm
2½ in.		2.5	2.36	1.34	2.16	3.00	.20	1.30	2.68	3.31	2.52	3.46	2.95	.14	in.
		63	60	34	55	76	5	33	68	84	64	88	75	3.5	mm

Standard Stem is ¼ NPT — Special on Request i.e. SAE straight thread swivel



Ordering Example: CF · 2P · 004 · B · SAE

***2" dia. gage has 2 mtg. holes on M dia.**

Can Flo Designation for Liquid Filled Gages

Size
1 — 2½ (63 mm)
5 — 2 (53 mm)

Type
C — Compound
V — Vacuum
P — Pressure

Range
002 — -30" Hg — 30 psi
000 — -30" Hg — 0 psi
002 — 0-30 psi
004 — 0-60 psi
007 — 0-100 psi
010 — 0-160 psi
015 — 0-200 psi
020 — 0-300 psi
035 — 0-500 psi
040 — 0-600 psi
055 — 0-800 psi
070 — 0-1000 psi
100 — 0-1500 psi
140 — 0-2000 psi
210 — 0-3000 psi
280 — 0-4000 psi
350 — 0-5000 psi
420 — 0-6000 psi
700 — 0-10 000 psi
800 — 0-15 000 psi

Style
A — Stem
B — Panel Clamp
D — Center or Lower Back
E — Panel Flange

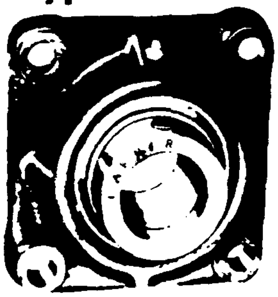
Connection
[illegible] NPT add SAE or BSP for these threads [illegible]

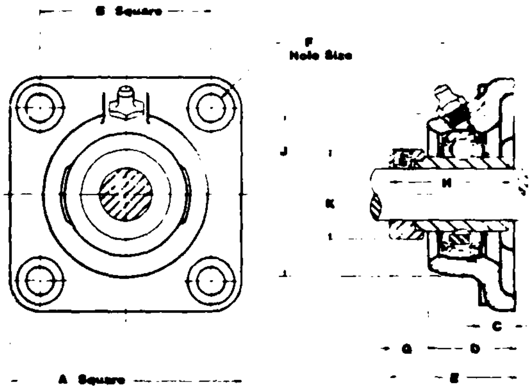
Note · 2 in. Gly. filled gage Special order only

Note · All stainless steel gages available · to order add 'SS' after model number

Flange Cartridges — Standard Series

RCJ • LCJ† • TCJ Types





Fafnir flange cartridges are used in applications where a minimum amount of machining is to be done. Each unit is furnished assembled and ready for mounting by means of bolts through the flange. They use a wide inner ring bearing, self-aligning B type, which compensates for shaft misalignment. RCJ type flange units are equipped with G-KRRB (R-Seal) wide inner ring bearings.

LCJ type flange units are equipped with G-KLLB (Mechani-Seal) wide inner ring bearings. TCJ units are equipped with G-KPPB (Tri-Ply Seal) wide inner ring bearings.

A grease fitting provides means of relubrication where required, a groove on the inside surface of the housing conducts grease to either of two holes in the bearing outer ring.

TO ORDER, SPECIFY UNIT AND SHAFT DIAMETER

Example: RCJ 1 7/16" or LCJ 1 7/16" or TCJ 1 7/16"

Unit and Shaft Diam. Inches	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	F	G	H	L	K	Bearing Number† RCJ	LCJ†	TCJ	Collar Number	Housing Number	Approx. Unit Wt. in Lbs.
*RCJ, LCJ 1/2 RCJ, LCJ 9/16 *RCJ, LCJ 5/8 RCJ, LCJ 11/16	3	2 1/8	1/2	1 5/32	1 37/64	25/64	31/64	1 15/32	2 1/16	1 1/8	G1008KRRB G1009KRRB G1010KRRB G1011KRRB	G1008KLLB G1009KLLB G1010KLLB G1011KLLB		S1008K S1009K S1010K S1011K	T-16659 T-16659 T-16659 T-16659	1.16
*RCJ, LCJ 3/4	3 3/8	2 1/2	1/2	1 1/4	1 51/64	25/64	35/64	1 23/32	2 3/8	1 5/16	G1012KRRB	G1012KLLB		S1012K	T-16661	1.60
RCJ, LCJ, TCJ 13/16 RCJ, LCJ, TCJ 7/8 *RCJ, LCJ, TCJ 15/16 *RCJ, LCJ, TCJ 1	3 3/4	2 3/4	9/16	1 5/16	1 27/32	29/64	17/32	1 3/4	2 9/16	1 1/2	G1013KRRB G1014KRRB G1015KRRB G1100KRRB	G1013KLLB G1014KLLB G1015KLLB G1100KLLB	G1013KPPB3 G1014KPPB3 G1015KPPB3 G1100KPPB3	S1013K S1014K S1015K S1100K	T-16663 T-16663 T-16663 T-16663	2.07
RCJ, LCJ, TCJ 1 1/16 RCJ, LCJ, TCJ 1 1/8 *RCJ, LCJ, TCJ 1 3/16	4 1/4	3 1/4	5/8	1 3/8	2	29/64	5/8	1 29/32	3	1 3/4	G1101KRRB G1102KRRB G1103KRRB	G1101KLLB G1102KLLB G1103KLLB	G1101KPPB3 G1102KPPB3 G1103KPPB3	S1101K S1102K S1103K	T-16664 T-16664 T-16664	2.87
*RCJ, LCJ, TCJ 1 1/4 RCJ, LCJ, TCJ 1 5/16 RCJ, LCJ, TCJ 1 3/8 *RCJ, LCJ, TCJ 1 7/16	4 5/8	3 5/8	21/32	1 15/32	2 1/8	33/64	21/32	2 1/64	3 1/2	2 3/16	G1104KRRB G1105KRRB G1106KRRB G1107KRRB	G1104KLLB G1105KLLB G1106KLLB G1107KLLB	G1104KPPB2 G1105KPPB2 G1106KPPB2 G1107KPPB2	S1104K S1105K S1106K S1107K	T-16617 T-16617 T-16617 T-16617	3.94
*RCJ, LCJ, TCJ 1 1/2 RCJ, LCJ, TCJ 1 9/16	5 1/8	4	11/16	1 19/32	2 5/16	33/64	23/32	2 7/32	3 7/8	2 3/8	G1108KRRB G1109KRRB	G1108KLLB G1109KLLB	G1108KPPB3 G1109KPPB3	S1108KT S1109KT	T-16666 T-16666	5.05
RCJ, LCJ, TCJ 1 5/8 *RCJ, LCJ, TCJ 1 11/16 RCJ, LCJ, TCJ 1 3/4	5 3/8	4 1/8	11/16	1 5/8	2 5/16	33/64	11/16	2 7/32	4 1/8	2 1/2	G1110KRRB G1111KRRB G1112KRRB	G1110KLLB G1111KLLB G1112KLLB	G1110KPPB4 G1111KPPB4 G1112KPPB4	S1110K S1111K S1112K	T-16667 T-16667 T-16667	5.70
RCJ, LCJ, TCJ 1 13/16 RCJ, LCJ, TCJ 1 7/8 *RCJ, LCJ, TCJ 1 15/16	5 5/8	4 3/8	23/32	1 7/8	2 5/8	33/64	3/4	2 15/32	4 7/16	2 3/4	G1113KRRB G1114KRRB G1115KRRB	G1113KLLB G1114KLLB G1115KLLB	G1113KPPB3 G1114KPPB3 G1115KPPB3	S1113K S1114K S1115K	T-16668 T-16668 T-16668	6.65
RCJ, LCJ, TCJ 2 RCJ, LCJ, TCJ 2 1/16 RCJ, LCJ, TCJ 2 1/8 *RCJ, LCJ, TCJ 2 3/16	6 3/8	5 1/8	25/32	2	2 31/32	41/64	31/32	2 13/16	4 3/4	3	G1200KRRB G1201KRRB G1202KRRB G1203KRRB	G1200KLLB G1201KLLB G1202KLLB G1203KLLB	G1200KPPB4 G1201KPPB4 G1202KPPB4 G1203KPPB4	S1200K S1201K S1202K S1203K	T-16683 T-16683 T-16683 T-16683	8.47
RCJ, LCJ 2 1/4 RCJ, LCJ 2 5/16 RCJ, LCJ 2 3/8 *RCJ, LCJ 2 7/16	6 7/8	5 5/8	21/32	2 11/32	3 1/4	41/64	29/32	3 1/16	5 3/8	3 5/16	G1204KRRB G1205KRRB G1206KRRB G1207KRRB	G1204KLLB G1205KLLB G1206KLLB G1207KLLB		S1204K S1205K S1206K S1207K	T-17648 T-17648 T-17648 T-17648	11.13
§*RCJ 2 11/16	7 3/8	5 7/8	23/32	2 1/2	3 1/2	41/64	7/8	3 3/8	5 7/8	3 13/16	G1211KRRB			S1211K	T-22270	15.18
RCJ, LCJ 2 15/16	7 3/4	6	7/8	2 5/8	3 25/32	25/32	1 5/32	3 5/8	6 3/8	4	G1215KRRB	G1215KLLB		S1215K	T-21620	13.10

* Preferred sizes.

§ Available only as RCJ with G1211KRRB bearing.

Recommended shaft tolerances: 1/2"-2" = Nominal to −.0005"
2 1/16"-2 15/16" = Nominal to −.0010"

† RCJ is recommended interchange with LCJ except in minimum torque or high temperature applications.

Unit	Bearing	Dimensions	Load Ratings
RCJ	G-KRRB	Page 148	Page 149
LCJ	G-KLLB	Page 156	Page 158
TCJ	G-KPPB	Page 160	Page 160

APPENDIX B

SAFETY REQUIREMENTS

89TECHD0031
June 6, 1988

HYDREX SAFETY GUIDELINES

The Hydrex system operates at pressures up to 60,000 psi and discharges water at a very high power level. As a result, the system has been designed with features to protect the operating personnel. However, certain safety precautions must also be taken. Listed below are design considerations and safety precautions:

Design Considerations:

Item:	Safety Considerations
1. High Pressure Tubing:	Tubing burst strength is approximately 120 ksi (2:1 safety factor). Failure mode is a longitudinal split in the tube wall.
2. High Pressure Hose:	Hose burst strength is approximately 120 ksi (2:1 safety factor). Failure mode is a rupture of the hose wall. As a result, the hose is jacketed with an outer hose to shield the burst.
3. High Pressure Fittings:	Burst strength is well over 120 ksi (2:1 safety factor). Failure mode is a longitudinal split in the wall with respect to the high pressure bore. Weep holes are also provided at each fitting connection for high pressure leaks.
4. Hydrex Vessel:	Burst strength is approximately 180 ksi. (3:1 safety factor) for the vessel wall or end closures. Failure mode is a longitudinal split in the wall or partial shear of the retaining pins in the end closure. Either failure mode causes a leak in the vessel which reduces internal pressure and prevents a catastrophic failure.
5. High Pressure Intensifier:	Burst strength is approximately 180 ksi (3:1 safety factor) or more for the vessel wall or end closures. Failure mode is a longitudinal split in the wall or shear of the end closure. Either failure mode causes a leak in the vessel which reduces pressure and prevents a catastrophic failure. Furthermore, the high pressure tubing serves to restrain end closures.

SAFETY PRECAUTIONS

1. All personnel must wear hard hats and safety glasses while operating or working in the vicinity of the Hydrex system.

2. All personnel must be at least five (5) feet from any high pressure components when operating at pressure, unless temporary adjustment or servicing is required.

3. All personnel must be at least twenty (20) feet from the high pressure drill while it is operating.

4. All personnel must be at least one hundred (100) feet from the Hydrex tool when firing, unless shielded by the backhoe or intensifier power unit.

5. Check that the high pressure fill line of the Hydrex tool is vented before attempting to disassemble the tool.

MK/DM/svp/1910a

APPENDIX C

DEFINITIONS (GLOSSARY)

APPENDIX C

DEFINITIONS (GLOSSARY)

ADMAC - ADvanced Mining And Construction Corporation.

Andesite - an intermediate composition volcanic rock typically found in back arc ranges such as the Cascade volcanos of the Northwest.

Bench - A bench-shaped excavation commonly found in quarries and open pit mines.

Burn hole - A hole drilled in the center of a blasting pattern to provide a free face and expansion room for the surrounding rock during blasting.

CAD - Computer-assisted design.

Deflagrating - An explosive that burns at velocities equal to or slower than the sound velocity.

Drilling jumbo - A large wheeled or tracked vehicle equipped with one or more booms used for drilling blast holes in a mining operation.

High explosive - Chemical explosives that detonate at velocities that excede the sound wave velocity.

HYDREX - HYDRaulic EXcavation tool.

Muck - The fragmented rock removed during excavation.

Piezo-transducer - pressure transducer based on the piezo-electric effect of charge separation due to stress.

Poppet valve - Hydraulic valve actuated by differential pressure.

Rayleigh wave - Seismic wave that propagates along the surface.

SBIR - Small Business Innovation Research program.

Scaling - To remove partially loosened rock from the excavation face.

TBM - Tunnel Boring Machine.

TNT - Tri-Nitro-Toluene, a high explosive.

APPENDIX D

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

APPENDIX D

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

b	constant
D	borehole diameter
G	shear modulus
J_s	energy per shot
K_m	bulk modulus of water
K_o	modulus of water at standard temperature (20°C) and pressure (1 bar)
M	mass of material
N	number of blasts
P	pressure
P'	pressurization rate
P_f	fracture pressure
P_p	peak pressure
S.E.	specific energy
t_p	pressure rise time
V	volume
V_o	initial volume
V_r	Rayleigh wave velocity
ρ	rock density
ρ_c	concrete density

APPENDIX E

INITIAL DISTRIBUTION LIST

MASTER ADDRESS LIST

SYMBOLS	MAILING ADDRESS
MYEB, PKRA	HQ BMO/ (Symbol) Norton AFB CA 92409-6468
DTIC	Defense Technical Information Center DTIC/FDA Cameron Station Alexandria VA 22304-6145
TRW/EDC	TRW/EDC P.O. Box 1310 San Bernardino CA 92402

Attachment 2 to
F04704-87-C-0032